Provincial Level Projection of the Current Mountain Pine Beetle Outbreak:

An Overview of the Model (BCMPB) and Draft Results of Year 1 of the Project

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1.0 Executive Summary

The BC Provincial Scale Mountain Pine Beetle Model (BCMPB) was developed as part of a two year project to assess the impacts of mountain pine beetle outbreak and management interactions across the entire province. This report describes the model and the results of the first year of work.

The model uses inputs from the forest cover inventory, management information, and mountain pine beetle provincial aerial overview maps. The main dynamics of the mountain pine beetle (*Dendroctonus ponderosae* MPB) outbreak sub-model were driven by the time series of overview infestation maps from 1999 to 2003, combined with information scaled up from the Canadian Forest Service stand model MPBSim (Safranyik et al. 1999) and the landscape scale model MPB-SELES (Fall et al. 2001). The management sub-model combines current and potential management activities across each timber supply area and tree farm licence, and is capable of processing a range of mountain pine beetle management activities such as leading-edge focus or salvage focus harvesting.

A range of scenarios was examined to assess the expected impacts of the outbreak under current and alternative management regimes. The main types of effects we assessed were mountain pine beetle impact indicators (volume and area affected or killed by mountain pine beetle), harvest indicators (volumes and areas harvested as green or salvage) and non-recovered loss indicators.

We considered one scenario as a *reference* that approximated current management at 2001/2002. We contrasted this with scenarios of alternative management (e.g. salvage focus, current management with no single-tree treatments, current uplifts in the allowable annual cut, etc.) and comparison scenarios (e.g. no harvesting, no beetle management).

The process of developing the model has highlighted some significant uncertainties in the "mountain pine beetle – forest management system". Primarily we are uncertain about:

- the levels of pine mortality that beetles may cause both at a stand and landscape level; and
- the rates of decay of dead pine as they relate to concerns about shelf life for various forest products.

The uncertainties in the system make it difficult to provide exact and unequivocal conclusions. Nonetheless we can conclude the following.

Previous research has shown that mountain pine beetle outbreaks are stopped by severe winter weather or depletion of the host. The vast spatial extent of the outbreak implies that a weather-stopping event is unlikely. The model projects that the current outbreak will continue to grow for three to four more years and then gradually decline over a period of 10 or more years. The model projects, as a worst case, that virtually all of the mature pine susceptible to mountain pine beetle

attack will be killed by 2020. Based on sensitivity analysis done to date we have no reason to expect that less than 80% of the pine will be affected.

Forest management, as modeled, does not alter the provincial scale spatial and temporal characteristics of the outbreak. In all scenarios the growing stock of pine in the province appears to be at substantial risk over the next two decades to significant decline due to the combined effect of mountain pine beetle attack and harvesting. Forest management has the potential to reduce the volumes killed by beetles by increasing the volume of green pine that is harvested. Focusing harvesting on salvage has the potential to reduce non-recovered losses.

Refinements on are ongoing to improve our confidence in the results. In the coming year we intend to thoroughly examine the sensitivity of various parameters in the beetle projection model and to make refinements and changes to that model as needed. We intend to engage a variety of domain experts in the field of forest management to help us specify and model various aspects of management with a focus on salvaging dead pine.

2.0 Introduction

Mountain pine beetles (*Dendroctonus ponderosae* MPB) are currently in the outbreak phase of the infestation cycle throughout much of their range in British Columbia. Adequate management of this provincial scale problem requires provincial scale knowledge. While we cannot hope to accurately predict the exact progression of the infestation, we can project a range of possibilities, given a variety of assumptions and uncertainties. Our hope is that these projections will help managers make more informed decisions about provincial and national level policies. Used appropriately, the results may also help guide actions at a management unit scale.

The landscape model described in this document was developed with support from the federal Mountain Pine Beetle Initiative, but we note that our work here builds upon the results of prior landscape modeling projects that were supported by a variety of sources. We would also like to acknowledge the contributions of Terry Shore, Les Safranyik and Bill Riel from Pacific Forestry Centre, Canadian Forest Service, upon whose expertise the mountain pine beetle models have been built.

This project can be described as a series of key steps:

- consulting with potential users to develop and refine the scope and objectives;
- obtaining geographic, forest inventory, forest management, weather and mountain pine beetle infestation data for the study area;
- analyzing the data to understand as much as possible about the course of the outbreak over the past five years;
- combining the results of our analysis with expert knowledge and results from more detailed fine-scale models to develop a provincial-scale projection model;
- projecting the outbreak forward given a range of management options and assumptions about beetles, and
- interpreting the projection results.

We investigated the course of the outbreak over a 20-year period, focusing mainly on the area affected and timber volumes killed by beetles, and the consequent effect on non-recovered losses and pine growing stock across the province. We did not include weather-stopping events, and so the results of this project are best viewed as a worst-case scenario.

We compared management scenarios to understand the benefits and impacts of various beetle management options. The mountain pine beetle outbreak and beetle management response affect a wide range of forest values. We did not attempt to analyze the implications of these impacts ourselves, as we believe that this is best done by topic experts (e.g. economists, caribou biologists). To this end, in

collaboration with interested users we have designed indicator files that can serve as input for further analysis of economic, social and/or ecological cost/benefits by interested topic experts.

3.0 Methods

3.1 Overall Landscape Model Design

The general design of BCMPB in terms of linkages between model state, landscape processes and output files is shown in Figure 1. The following description summarizes the structure, operation and data requirements of the model. More detailed description of the management sub-model, including planning and harvesting, and the mountain pine beetle growth and dispersal sub-model are provided in Appendix 2 and Appendix 3 respectively. A detailed discussion of the input data is provided in Appendix 1.

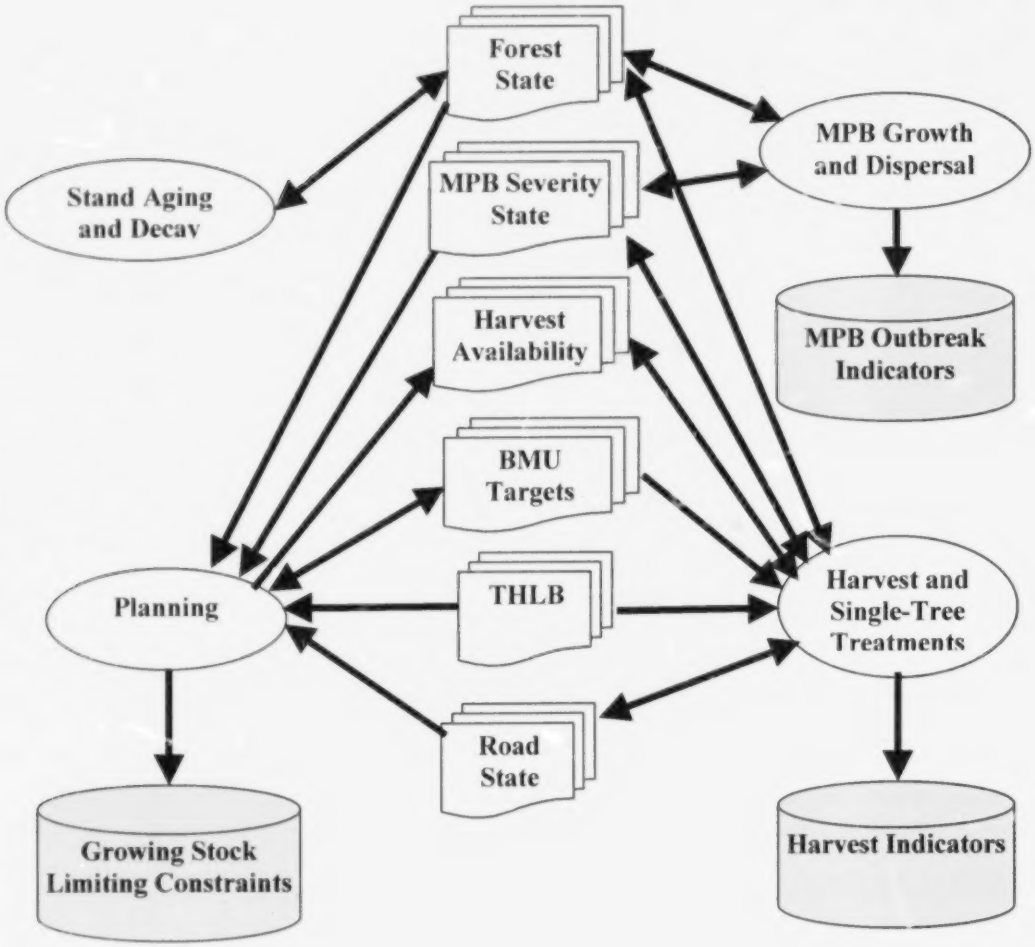

Figure 1. Linkages between primary components of state (shown in the centre), model processes (shown in ovals) and output files (shown as grey drums).

3.1.1 Model State Space

The following data layers comprise the model state space. Each spatial variable is represented by a grid of 16 hectare cells that are homogenous with respect to the layer attributes.

Landscape structure: the landscape biogeographical context and the limits of the study area are defined with the following spatial variables:

(i) BEC: biogeoeclimatic classification by variant.
(ii) Elevation: elevation in metres

Forest State: the forest is represented by the following layers:

(iii) Age: age in years (projected to start year).
(iv) ITG: inventory type group (leading and secondary species).
(v) VolPerHa: standing volume/ha for trees greater than 12.5 cm dbh (as reported in the inventory database).
(vi) PineVolPerHa: standing volume/ha that is pine greater than 12.5 cm dbh.
(vii) Percent pine: PineVolPerHa divided by VolPerHa
(viii) SalvageableVolumePerHa: amount of salvageable volume in each cell.
(ix) MPB Susceptibility: estimated according to the index developed by CFS (Shore and Safranyik, 1992), but lacking stand density.

Mountain Pine Beetle Severity State:

(x) State of attack in each cell: represented using broad classes similar to those in the provincial aerial overview data: based on the percent of pine in each cell that has been attacked: no mountain pine beetle (0% attack), endemic (<1% attack), low (1-10% attack), medium (10-20% attack) and severe (> 20% attack).

Harvest Availability:

(xi) PotentialTreatmentType: the available forest is stratified into the type of treatment that would be applied if a harvest block were initiated at that cell. Valid treatments are discussed below.

Timber harvesting landbase:

(xii) THLB: the timber harvesting landbase is derived from the productive operable forests by using a netdown process that removes forest for various reasons, applied spatially. Individual cells are either completely within or without the THLB. The majority of these reasons for removal will generally remove entire cells (e.g. non-merchantable forest), but some may remove only portions of a cell (e.g. roads, riparian zones). In these latter cases, we chose whether to include or exclude a cell randomly using a probability equal to the proportion.

Management Zones:

(xiii) MgmtUnit: management unit (TSA or TFL)
(xiv) LU: Landscape Units
(xv) BMU: beetle management units
(xvi) VQO: visual quality objective zones.

Management Parameters: A range of parameters and tables represent the harvesting regime, including:

(xvii) AAC (annual allowable cut): the "target" for the area to be harvested per year for each management unit. For TSAs this was obtained directly from the most recent Timber Supply Analysis report. For TFLs the volume target was converted to an area based on average volumes per hectare.
(xviii) BMUStrategies: beetle management unit strategies described below.
(xix) Minimum harvest volume: generally 150 m^3 per ha except for salvage.
(xx) Management constraints: described below
(xxi) Management preferences: described below

Roads:

(xxii) DistanceToRoads: distance to existing roads in metres.

3.1.2 Stand Aging and Decay

This event increments stand age each time step (one year), and updates the susceptibility rating estimate. The model does not capture changes in tree species or the growth of trees through time. This event is also responsible for applying decay (currently combining ecological and economic decay) of salvageable wood. The next version of the model will separate these two factors. Economic decay depends on markets and target products, and hence in some cases ought to be interpreted post-simulation.

3.1.3 Mountain Pine Beetle Outbreak Model

The mountain pine beetle outbreak sub-model is a discrete state change model. In each year at each location the mountain pine beetle will be in one of five states. The states are based on percent of pine trees in 16-ha cells that are currently (current severity) or cumulatively (cumulative severity) attacked:

1. NoMPB: 0% attack
2. Endemic: 0-1% attack
3. Low: 1-10% attack
4. Moderate: 10-20% attack
5. High: 20-100% attack

These classes are similar to those used in the overview survey, except we have added an additional class (Endemic) for very low attack levels, and decreased the threshold between moderate and high from 30% to 20%.

In each year of a simulation, the current mountain pine beetle state in each cell may remain the same, or change to more or less severe states. The probability of a given beetle state arising depends on the previous year's state, the cumulative amount of kill by beetles, host conditions in the cell, external mountain pine beetle pressure, and management effects. The state-to-state transition matrix is parameterized using observed transition probabilities in the overview data from 1999 to 2003, supplemented by information from the landscape scale (MPB-SELES) and stand scale (MPBSim) models.

Previously un-attacked cells (NoMPB state) may be subject to local beetle dispersal pressure from nearby cells, long-distance pressure from cells many kilometers away, or no significant beetle pressure at all. There is some probability that infestations will arise "spontaneously" in areas not subject to significant dispersal pressure, presumably due to local increase in endemic beetle populations. We modify the beetle dispersal model from the landscape scale MPB-SELES model to estimate beetle dispersal pressure across the province. There is little information available on the long-distance dispersal behaviour of beetles, so that portion of the model is based on the observed ability of proximity of cells to existing outbreaks, relative to prevailing wind, to explain infestation starts in the past overview data (i.e. we do not presuppose the effect that dispersal pressure will have on the probability of infestations arising).

Currently attacked cells may increase or decrease their infestation severity depending on current infestation severity, depletion of hosts, and external beetle pressure. Owing to the relatively short time-depth of our data, and various other problems with applying the overview survey to this application, we rely mainly on the behaviour of the district scale model MPB-SELES to predict the progress of infestations once they have begun.

The primary effect of mountain pine beetle attack is to shift living pine volume to standing dead volume (salvageable wood). By killing trees, mountain pine beetle become indirectly visible to the management sub-model, thereby influencing the focus of harvest, single-tree treatments and BMU ratings.

3.1.4 Planning

This event performs an inventory analysis each time step. It tracks the amounts of forest old enough to harvest (merchantable), available subject to road access and visual constraints, and determines which cells are available for harvest. Note that the only forest cover constraint applied was for visual objectives (e.g. no rules for ungulate winter range, caribou, community watersheds, etc. were applied). For

cells that are unavailable, this sub-model outputs information to determine which constraint(s) were responsible.

The second key task of this sub-model is to establish beetle management unit (BMU) types. The possible types, and general management policies are:

- *Monitor:* no beetles present; focus on green tree harvest
- *Suppression:* low to moderate mountain pine beetle; focus on reducing populations
- *Holding Action:* moderate to high mountain pine beetle; focus on reducing populations
- *Salvage:* high to very high mountain pine beetle, or post-outbreak collapse: focus on recovering standing dead volume.

For each BMU, an "outbreak level index" (*BMU rating)* was computed as follows:

Area with endemic mountain pine beetle state / area with mountain pine beetle > endemic

This index roughly corresponds to a spot:patch ratio. BMUs are processed sequentially in increasing order of this index. If there are no detectable mountain pine beetles, then a BMU is assigned a *monitor* type. If the single-tree budget (after reductions for previously processed BMUs) is capable of addressing at least 80% of the endemic cells, then a BMU is assigned a *suppression* type. Otherwise, if the BMU rating is < 0.2 (i.e. at most 80% of the attack is in higher mountain pine beetle attack states) and the total area attacked in the BMU is less than 5,000 ha, then the BMU is assigned a *holding action* type. Finally, unassigned BMUs are assigned a *salvage* type. See the following sub-models for details on how provincial single-tree budget, and management unit AAC is partitioned among BMUs, and how BMU types influence targeted harvesting.

3.1.5 Harvesting

This event performs forest harvesting simultaneously in each TSA/TFL in the province. Each management unit is processed independently, and so this sub-model can be described from the perspective of a single unit. In each unit, the target allowable annual cut (AAC), expressed using area, is harvested from the available cells.

Each year, the target area or volume AAC provides a "beetle management potential". How this is allocated across a unit depends on the BMU ratings, mountain pine beetle state, stand ages/volumes and salvage volumes, and is designed to capture the fundamentals of bark beetle management (MOF and BCE 1995). The available cells in the unit are stratified into groups based on BMU rating and mountain pine beetle outbreak state, and processed according to a priority order. Within each stratum, ordering is according to stand age or

salvagable volume. The following describes the strata, from highest to lowest priority within a management unit:

- Low and moderate mountain pine beetle in suppression BMUs: focuses harvesting on leading edge attack.
- Endemic and severe mountain pine beetle in suppression BMUs: focuses harvesting on other mountain pine beetle attack in suppression BMUs.
- Low and moderate mountain pine beetle in holding action BMUs: focuses harvesting on leading edge attack
- Severe mountain pine beetle in holding action BMUs: focuses harvesting on high populations
- Salvage in salvage BMUs: areas with adequate salvage (> $50m^3$/ha)
- Moderate and severe mountain pine beetle in salvage BMUs: focuses harvesting on areas likely to result in substantial salvage
- Salvage in other BMUs, and low and endemic mountain pine beetle in salvage BMUs: remaining "mop-up" classes
- Green harvest (no mountain pine beetle) in any BMU: regular green harvest

In cases of salvage, prioritization within the stratum will be according to amount of salvageable wood, while in all other cases prioritization will be according to age. Hence in units with no mountain pine beetle (i.e. all BMU types will be *monitor*), all harvesting will be "green harvest", and hence according to "oldest-first, nearest to road". In management units with a mixture of BMU types, the actual allocation of harvesting will primarily focus on reducing populations, followed by salvage. In management units dominated by salvage BMU types, harvesting will be "highest salvage-volume first, nearest to road".

The default cutblock size was up to 16-32ha (1-2 cells), based on a spatial assessment of recent block sizes in different regions of the province, and on the bark beetle regulations.

Where blocks are placed, volume (green and salvage) is recuperated, harvest indicators are updated, mountain pine beetle state is reset to "no mountain pine beetle" (i.e. the model assumes close to 100% efficacy), stand age is reset to 0, and visual targets are updated. In addition, this sub-model explicitly connects cutblocks to the main road network by adding a link from the first cell harvested in a block to the nearest existing road. It then updates a map indicating the distance from each cell to the nearest existing road. This step permits estimation of the amount of road constructed under a given management regime, and to determine accessibility in future time steps.

3.1.6 Single-Tree Treatments

This sub-model simulates fell and burn and MSMA treatment methods in each *suppression* BMU of the province simultaneously. First the provincial budget is allocated among *suppression* BMUs proportional to the level of endemic

mountain pine beetle state. As with the logging sub-model, the model description can be then cast from the perspective of a single BMU. Single-tree treatments are generally applied in inaccessible areas or areas with low (endemic and some low mountain pine beetle state) beetle populations. These treatments are applied to individual cells, and the volume is not recovered. The model assumes that the mountain pine beetle state is reduced by one level (i.e. endemic state becomes "no MBP", while low becomes endemic).

3.2 Model Outputs

The model outputs relevant to this analysis are described below. A description of the indicator files produced for each of the principal clients of the project is found in Appendix 4.

3.2.1 Mountain Pine Beetle Outbreak Indictors

MPB report: A range of output values that track key aspects of the mountain pine beetle outbreak for each management unit:

- Overall area attacked
- Number of hectares in each severity class
- Cumulative proportion of pine killed
- Volume killed
- Salvageable volume

3.2.2 Inventory Indictors

Growing Stock: Growing stock is the cubic metres of live forest in each management unit in various strata of the landbase (overall, pine, in the THLB, available, merchantable). Also output are salvageable volume and non-recovered losses.

Limiting Constraints: Track the area of forest made unavailable in each management unit for harvest according to the various constraints. This is output as net and gross values, where the net value is the incremental area constrained after preceding constraints have been accounted for, and the gross value is the total amount the would be constrained independent of the other constraints. The primary order of constraints applied is:

- minimum harvest age
- road access (if enabled)
- adjacency (if enabled)
- VQO constraints
- Available after all constraints have been applied

3.2.3 Harvest Indictors

Harvest Report: A range of output values that track key aspects of the harvesting process overall, for each management unit and for each landscape unit:

- annual volume harvested
- annual area harvested
- mean volume per hectare harvested
- percent of harvest target achieved
- mean age harvested
- kilometers of roads built
- area harvested by mountain pine beetle severity state and salvage
- area processed with single tree treatments

BMU report: Values that track key aspects of BMU management:

- BMU type (strategy applied)
- Number of hectares treatable with single tree
- Single tree budget applied in BMU
- Proportion of provincial single tree budget
- Number of hectares actually treated with single tree

3.2.4 Spatial output

The client specific indicator files are described in detail in Appendix 4. These files are generated in a post-simulation step using spatial time series of layers output from BCMPB during a run. This is done to keep the underlying dynamics in BCMPB as simple and clear as possible, to improve efficiency, and to allow changes in indicator strata without requiring that we re-run the main model. The following layers are output annually during each simulation:

(i) *Stand age*: age of forest in each cell
(ii) *BMU type*: type of each BMU as assigned during the planning sub-model.
(iii) *mountain pine beetle severity*: current mountain pine beetle severity class of each cell
(iv) *mountain pine beetle cumulative severity*: cumulative mountain pine beetle severity class of each cell
(v) *Time since attack*: number of years since cell was last attacked
(vi) *Volume per hectare*: cubic metres/ha in each cell (live growing stock)
(vii) *Pine volume per hectare*: cubic metres/ha of pine in each cell (live growing stock)
(viii) *Salvageable volume per hectare*: cubic metres/ha of merchanable standing dead volume in each cell.
(ix) *Green harvest volume*: cubic metres/ha of green (live) forest harvested in each cell
(x) *Salvage harvest volume*: cubit metres/ha of salvage harvested in each cell
(xi) *Non-recovered loss volume per hectare*: cubic metres/ha of salvageable volume lost to economic decay in each cell

3.3 Scenarios Evaluated

A range of scenarios was run to verify the model prior to running the main scenarios described below. These verification scenarios led to model improvements and refinements, as well as greater understanding of the model interactions and feedback. We don't describe the results of the verification runs here, and instead focus on scenarios that produced information relevant for project objectives. Some details of the verification of the model can be found in Appendix 5.

At the level of a single grid cell, the behaviour of BCMPB is highly stochastic. However, over the 982 thousand susceptible forest cells in British Columbia this stochasticity averages out, so the main indicators are largely stable between runs at the provincial scale. We ran each scenario for one replicate, but expect to assess how variation in multi-replicate runs affects our results in the upcoming year.

The key scenarios used to assess management alternatives are as follows

Scenario Name	Description
BM_Reference	2001/2002 AAC (i.e. no uplifts), plus current levels of single tree treatments. Focus on leading edge attack where possible, and salvage elsewhere
BM_Uplift	Same as reference scenario, but increase AAC in specific management units with uplifts as determined by the chief forester
BM_NoSST	Same as reference scenario, except apply no single tree treatments
Salvage_HighestVol	Focus on salvage. Same harvest levels as reference scenario. Effectively, treat each BMU as if it was assigned a *salvage* type. Salvage is only allowed where there is more than 50 m^3 per hectare of dead pine
Salvage_HighestProp	Same as salvage scenario, except focus harvest on stands with highest proportion of salvage:green vs. highest amount of salvageable wood.

Several other scenarios were run, not as plausible management options, but rather to provide a context for comparing the main scenarios.

Scenario Name	Description
NoMgmt	Apply no harvesting nor single-tree treatments
NoBM	Harvesting using general management rules, but ignoring mountain pine beetle and salvage
BM_DoubleCut	Double annual harvest rates in all management units in the province. Otherwise same as reference scenario.
SalvageExt	Extreme salvage. Same as the Salvage_HighestVol scenario, but allow salvage harvest of any stand with at least 1m3/ha of salvageable wood

4.0 Results and Discussion

4.1 Forests at Risk to Mountain Pine Beetle

We estimate that there are a total of 9.9 billion m^3 of timber with a diameter at breast height greater than 12.5 cm (the "primary utilization level") in the province of British Columbia (Table 1)[1]. Of this slightly less than one quarter is one of the 5 pine species found in the province (Limber, Lodgepole, Western White, Whitebark or Ponderosa Pine; *Pinus flexilis, contorta, monticola, albicaulis*, or *ponderosa*, respectively). However, the proportion of pine on the timber harvesting landbase (30%) is much higher than on the non-contributing landbase (18%) (Table 1).

Of the total pine volume in the province approximately 1.9 billion m^3 is susceptible to mountain pine beetle attack (Table 2), by our definition (older than 60 years and in climatically suitable Biogeoclimatic zone – i.e. not AT, BWBS, CDF, CWH, SWB). Although mountain pine beetle has caused significant damage to coastal pine in the past (Collis and Alexander 1966) we find it convenient to exclude these areas for the purpose of this analysis primarily because there the current outbreak has not yet developed a significant coastal component. Of the 1.9 billion m^3 of susceptible pine 1.2 billion m^3 is in the timber harvesting landbase. This represents the timber volume "at risk" of loss.

Table 1. Billions of cubic metres of timber volume in British Columbia prior to the outbreak

	timber harvesting landbase		
	No	Yes	Total
Pine	0.97	1.36	2.33
Other Species	4.33	3.22	7.55
Total	5.30	4.58	9.88

Table 2. Billions of cubic metres of pine volume in British Columbia prior to the outbreak

	timber harvesting landbase		
Susceptible to mountain pine beetle	No	Yes	Total
No	0.33	0.14	0.47
Yes	0.64	1.21	1.85
Total	0.97	1.35	2.32

The forested area of British Columbia is approximately 61.6 million hectares. Of that area 33.1 million hectares are in the Biogeoclimatic Zones that are

1 Our estimates of volumes and areas are based on a combination of data sources as described in Appendix 1.

climatically suitable for mountain pine beetles (see above). Forty six percent of the total forested area in the province contains some pine. In the susceptible BEC Zones 60% of the forest stands contain some pine component (Table 3).

Table 3. Forested area with and without pine in the susceptible Biogeoclimatic Zones (millions of hectares).

	timber harvesting landbase		
Tree Species	No	Yes	Totall
No Pine	7.6	5.6	13.2
With Pine	8.1	11.8	19.9
Total	15.7	17.4	33.1

The proportion of pine in forested stands varies significantly throughout the province (Table 4). Throughout the susceptible BEC Zones 39% of the pine is in forests with a high (>=90%) pine but almost 30% is in areas with less than 40% pine. Again, these percentages are highly variable throughout the province.

Table 4. Percentage of pine in stands in the susceptible BEC Zones and selected TSAs

Percent Pine	Entire Susceptible Area	Arrow TSA	Quesnel TSA
Low (<40%)	29%	59%	13%
Moderate (40 - 89%)	32%	31%	26%
High (90 - 100%)	39%	10%	61%
Total	100%	100%	100%

4.2 Volume and Areas affected by mountain pine beetle in 2003

Based on the provincial aerial overview surveys we estimate that a total of 164 million m^3 of pine have been killed by mountain pine beetle as of 2003. This estimate is for the "observable" (red) dead pine and does not include estimates of "green attack". Of that, 106 m^3 were in the timber harvesting landbase (9% of the total susceptible volume). The area affected by mountain pine beetle is difficult to easily summarize because of the variability in proportion of the pine that is affected in any given place. We estimate that approximately 1.2 million hectares of forest were in an "incipient" stage of infestation (> 0 and <1% of the pine killed) in 2003. Approximately 5.5 million hectares had experienced more than 1% of the pine killed by 2003. This represents 40% of the area of susceptible pine. This estimate is much higher than the 4 million hectares estimated by the provincial aerial overview data in 2003 (Anon 2003) because that estimate only includes the current annual attack, rather than the cumulative attack over all years, and because the method we use to convert the polygon based aerial overview data to a grid based map tends to increase the apparent area of the attack even though it has no effect on the overall volume of the attack. According to our grid-based data, the area infested by beetles in 2003 is approximately 4.3 million hectares, so

converting polygon to raster data increases the apparent infested area by 8%. The majority of susceptible pine forest had experienced little or no mortality by 2003 (Table 5). However, the amount of pine killed is highly variable throughout the province (Table 5, Figure 2). The major concentration of kill by mountain pine beetle in 2003 was centered on the Quesnel, southeastern Nadina and Vanderhoof Forest Districts

Table 5. Proportion of area with pine by class of cumulative kill for all susceptible pine and selected management units

Cumulative Kill at 2003	All Susceptible Pine	Arrow TSA	Quesnel TSA
No kill	65%	79%	25%
>0 and <1%	7%	8%	2%
1 - 20 %	17%	10%	36%
21 -50 %	7%	3%	27%
51 - 75 %	3%	0%	7%
76 - 100 %	1%	1%	3%
Total	100%	100%	100%

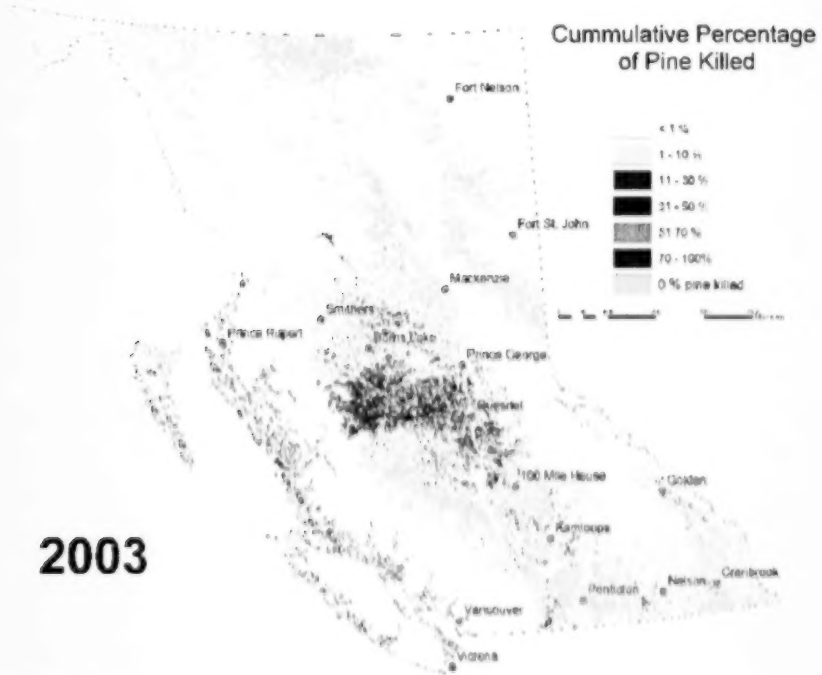

Figure 2. Observed cumulative percentage of pine killed in 2003

(A high resolution (3 meg.) version of this figure is available http://www.for.gov.bc.ca/hre/BCMPB/BCMPB_pctkill2003_Input.pdf)

4.3 Projection of the Reference Scenario.

We project that the annual volume of pine killed will peak during 2007 or 2008 at more than 70 million m^3 of pine in the timber harvesting landbase (Figure 3). Significant volumes of pine will continue to be killed at least until 2015 and we project that the volume killed will not decrease to pre-outbreak levels until after 2020. In general the outbreak initially expands rapidly for several years because it currently is centered on very high quality beetle habitat (large areas of continuous mature pine). The outbreak subsides as that habitat is depleted and the beetles move into less desirable habitat (smaller areas of more dispersed pine). Our projections are based on the understanding that the provincial aerial overview data over estimates the volumes killed in severely infested areas (Ebata, pers. comm.). As a result our projection of the annual kill does not "follow" the apparent trend in the overview data (Figure 3). Both our representation of the overview data and the model projections include this understanding.

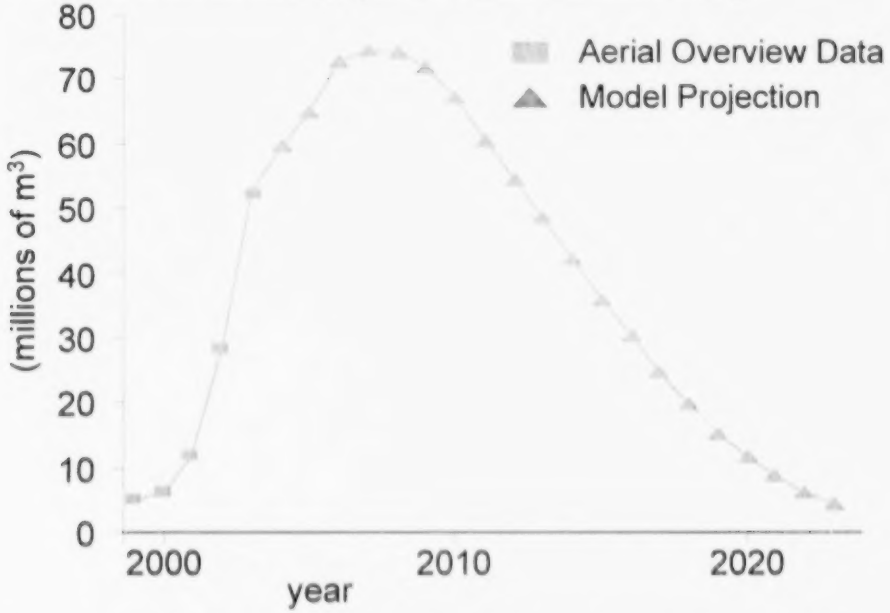

Figure 3. Observed and Projected (for the Reference Scenario) Annual Volume of Pine Killed in the Timber Harvesting Landbase.

We project substantial variability in the timing of the peak in annual kill in different areas of the province (Figure 4). Figure 4 shows the annual kill for each Timber Supply Area. The management units are listed on the right in descending order of the proportion of pine killed in 2003. Those units with the higher proportions of pine killed have an earlier peak in annual kill. Quesnel has the highest proportion of pine killed in 2003 (25%) and is the only management unit that has already passed the peak in annual kill. Units with lower proportions of pine killed are generally further from the center of the outbreak and thus take

longer to experience the peak in annual kill. In general, the later the occurrence of the peak in annual kill the lower the percentage of pine that is killed at the peak. We attribute this to the fact that those units that peak late tend to have relatively poor, discontinuous beetle habitat.

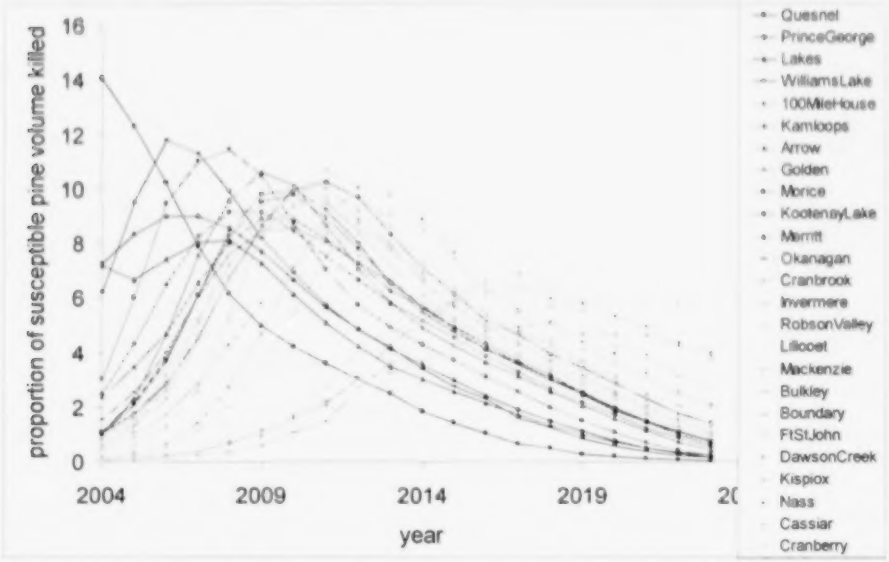

Figure 4. Effect of initial proportion of volume killed on the progression of the outbreak.

The Reference Scenario projects that well over 90% of the susceptible pine on the timber harvesting landbase will be killed by 2020 (Figure 5). It should be noted that this effectively represents a "worst case" scenario. The projection indicates how long it would take to get as bad as it could possibly get. Past outbreaks of mountain pine beetle have been "stopped" by very cold winters (Wood and Unger 1996). It is not inconceivable that cold winters may slow or stop the progression of this outbreak. However, it is very unlikely that the entire outbreak area will experience sufficiently cold weather to affect a significant proportion of the beetle population. Our projection may also represent an over estimate because we project that virtually all the volume within all stands will eventually be killed by mountain pine beetle. Appendix 5 describes sensitivity tests in which this assumption is relaxed by not allowing the infestation to "re-start" in cells where it had subsided completely even if there remained susceptible pine. This modification to the model results in projections of approximately 80% of the susceptible volume being killed by 2020.

We are not aware of any systematic survey of kill rates that could definitively tell us what proportion of trees might be killed by beetles in a typical outbreak, but the suggestion from beetle researchers is that beetles rarely kill more than 90% of the volume in a stand. From their collective experience, researchers from the

Canadian Forest Service suggest that, in pure pine stands subject to heavy beetle pressure, 70% of the stems and 90% of the standing volume might be killed by beetles. Over the whole landscape, they suggest the average is probably closer to 50-60% of the stems and 60-70% of the volume (T. Shore, pers. comm.). An incomplete survey of the literature corroborates these opinions: 32-92% of merchantable basal area killed in 10 study areas in Wyoming and Idaho (Amman and Baker 1972); 50 – 75% of stems killed in 40 stands in Northern Utah (Stone and Wolfe 1996); and 41- 67% of stems killed in 10 stands in southwestern Yellowstone (Romme et al 1986).

In addition to the opinion of CFS researchers and a few corroborating studies, there are good biological reasons to expect that beetles will not kill all trees. Even within uniform-aged pure pine stands there is variation in tree diameter and vigour. Smaller trees tend to have thinner phloem, which provides beetles with less food, and also protects them less well from drying out (Safranyik et al 1999). Beetles tend to attack large trees first (Geiszler et al. 1980; Mitchell and Preisler 1991), where they can reproduce successfully. Once they have exhausted the quality food supply, they turn to smaller trees, but will survive less well in these trees, causing populations to decline before all the small trees can be killed. Beetles might also tend to do poorer in stands with fewer live pine trees. It has been established that thinning lodgepole pine stands reduces forest susceptibility to beetles (Amman et al. 1988; Mitchell et al. 1983; Preisler and Mitchell 1993; Waring and Pitman 1985). This might be because the vigour of trees increases in less crowded stands, because it is more difficult for beetles to switch between trees that are further away from one another, or because the microclimate in more open stands is less good for beetles. Whatever the reason, it is reasonable to expect that stands thinned by previous beetle mortality are also less good for beetles.

We are currently working on refinements to the mountain pine beetle projection sub-model to reflect the variability in estimates of percentage kill within stands.

By 2008, at the projected peak in annual kill, our model estimates that 10.2 million ha of susceptible pine (72%) will be infested by mountain pine beetles and over 400 million m^3 of pine on the timber harvesting landbase will have been killed (Figure 5). That area will be distributed throughout the susceptible range with concentrations of current attack in the northern and southern portions (Figure 6)

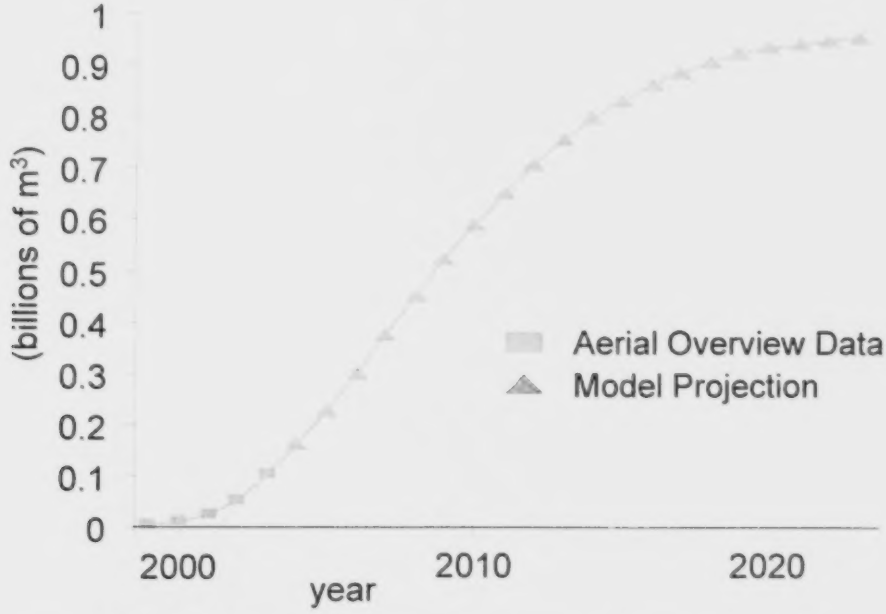

Figure 5. Observed and Projected (for the Reference Scenario) Cumulative Volume of Pine Killed in the timber harvesting landbase

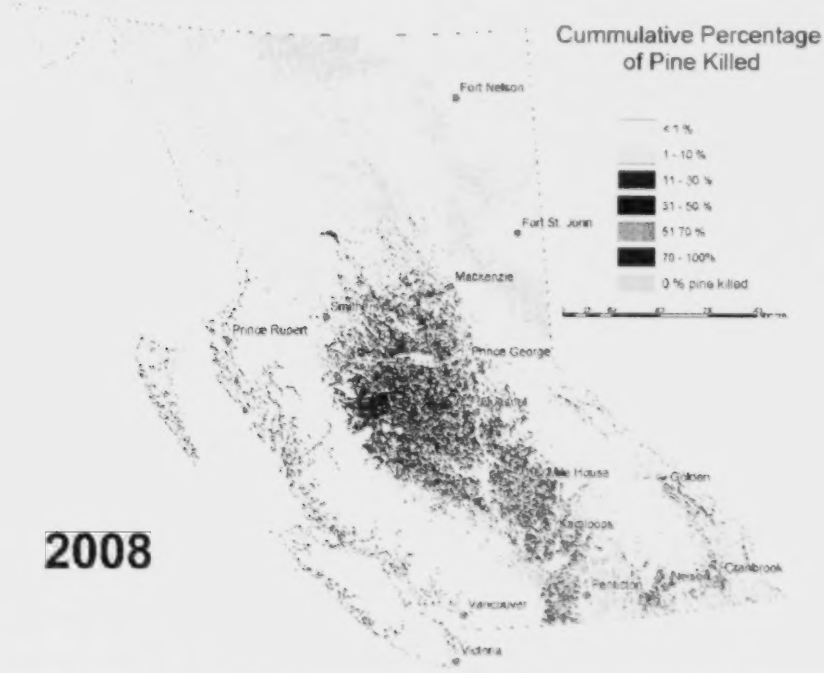

Figure 6. Projected cumulative percentage of pine killed in 2008 under the reference scenario

(A high resolution (3 meg.) version of Figure 6 is available http://www.for.gov.bc.ca/hre/BCMPB/BCMPB_pctkill2008_Input.pdf)

Figure 7 illustrates the effect of the mountain pine beetle outbreak and associated management activities on pine volume within the timber harvesting landbase . As a worst case scenario, we project that less than 20% of the total pine volume in the province will remain living after 20 years. That is, only the non-susceptible pine will remain living. A significant proportion of the remainder will be harvested, either as green volume or as salvage, but almost half the volume will become "non-recovered" losses.

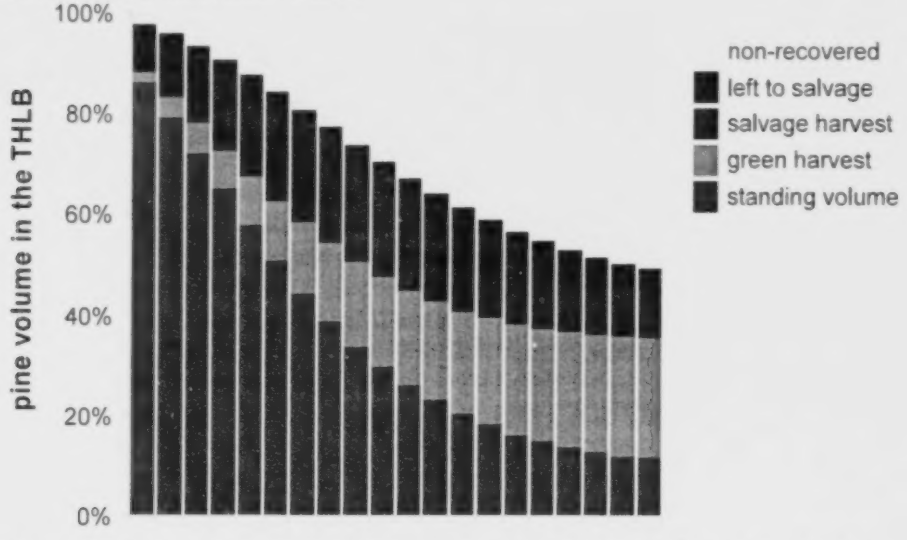

Figure 7. Projected proportion of pine volume on the timber harvesting landbase in various categories under the Reference Scenario

4.4 Comparison of Beetle Management Scenarios

We constructed and projected four beetle management scenarios as described in Section 3.3:

1. BM_Reference: the reference scenario with the application of beetle management strategies and the AAC as of 2001/2002
2. BM_Uplift: the reference scenarios with uplifts in the AAC as of January 2004
3. BM_NoSTT: the reference scenario with no single tree treatments.

We include three more scenarios for comparison purposes only. These are not meant to be plausible alternatives but rather are meant to place "bounds" on the problem:

1. NoMgmt: No forest harvesting – just the beetle outbreak

2. NoBM: Forest harvesting based on oldest first harvesting rules rather than any applying any beetle management or salvage strategies.
3. BM_DoubleCut: the reference scenario with twice the AAC in all management units.

The difference in the projected annual kill among scenarios is presented in Figure 8. We would expect that if beetle management strategies were slowing the outbreak then the peak in annual kill would occur at later times in scenarios with more aggressive beetle management. Note that, with the exception of BM_DoubleCut the peak in annual kill occurs at the same time for all the scenarios – at 2008. This indicates that beetle management, as modeled, does not slow the outbreak at a provincial scale. In fact the most aggressive beetle management scenario, BM_DoubleCut, moves the peak forward two years, while decreasing its amplitude. This is because the substantial increase in harvest level serves to more quickly reduce susceptible hosts. Note also that, as expected, the height of the peak in annual kill is depressed as more aggressive beetle management is imposed. Single tree treatments do have an effect on the height of the peak in annual kill but have no effect on the amount of kill as the infestation subsides.

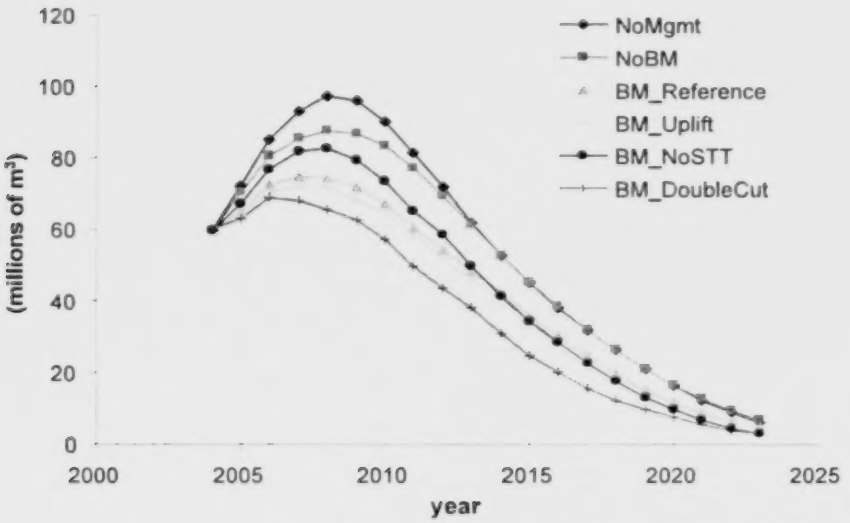

Figure 8. Comparison of projections in annual volume of pine killed on the THLB among beetle management scenarios.

There is some variability throughout the province in the impact that beetle management has on the outbreak. In areas near the center of the province, the provincial scale conclusions hold (see for example100 Mile House in Figure 9). However, at the periphery of the outbreak (see for example Cranbrook in Figure 9) beetle management does appear to have the desired effect. That is, the peak in annual kill occurs later as beetle management is implemented and single tree treatments depress the amount of kill throughout the outbreak. This is consistent

with the findings of modeling work done at district scales in the Lakes District, near the center of the outbreak (Fall et al. 2002) and Kamloops and Morice Districts, at the periphery of the outbreak when the modeling was done (Fall et al. 2001; 2003a).

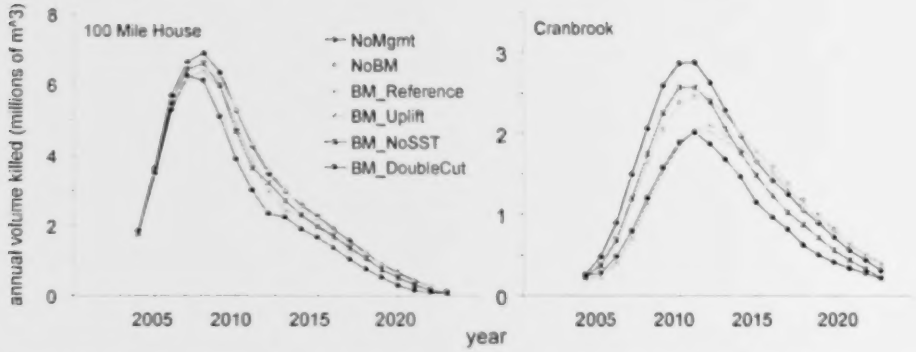

Figure 9. Comparison of projections in annual volume of pine killed on the THLB in the 100 Mile House and Cranbrook TSAs among beetle management scenarios.

Figure 10, Figure 11 and Figure 12 illustrate the projected cumulative effect of the mountain pine beetle outbreak and the beetle management activities on the volume of standing pine on the timber harvesting landbase. Figure 10 shows a comparison of the cumulative volume of pine killed on the THLB among scenarios. As expected, the no management (no harvesting) and no beetle management scenarios have the highest cumulative kills. By concentrating harvest on pine, as is done in the other four scenarios, we appear to have a positive impact on the volume of pine killed. As an aside, note that, over the course of the infestation, single tree treatments have little impact on the total volume killed. Examining Figure 11 shows that in order to have the "desired" effects on beetles we must harvest pine. That is, achieving lower cumulative kill by beetles is only accomplished by a concomitant increase in the harvest level of green pine. The result is that, regardless of the effort expended on beetle management, the combined impact on the standing volume of pine is virtually the same (Figure 12). This result indicates that, at a provincial scale and given the extent and severity of the outbreak, beetle management appears to have little effect on the overall impact of the outbreak with respect to future timber supply considerations.

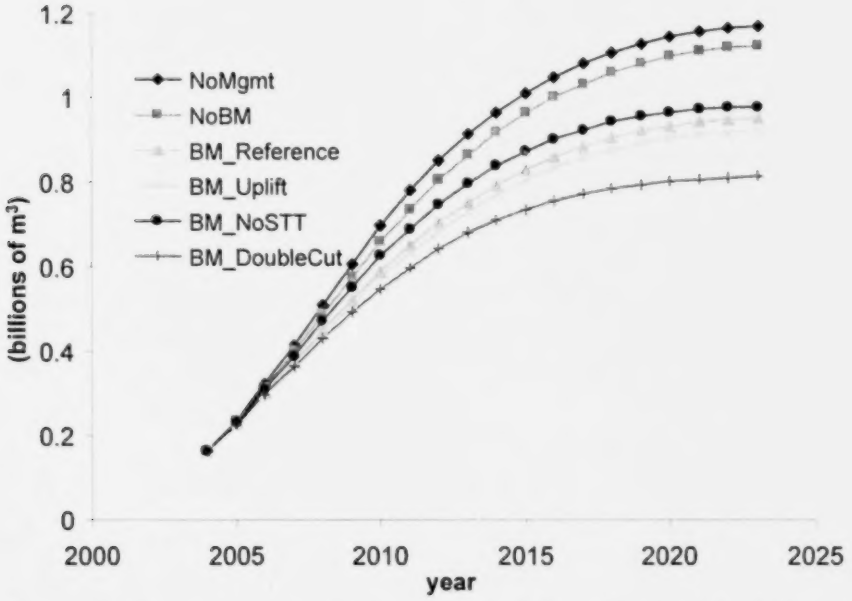

Figure 10. Comparison of projections in cumulative volume of pine killed on the THLB among beetle management scenarios.

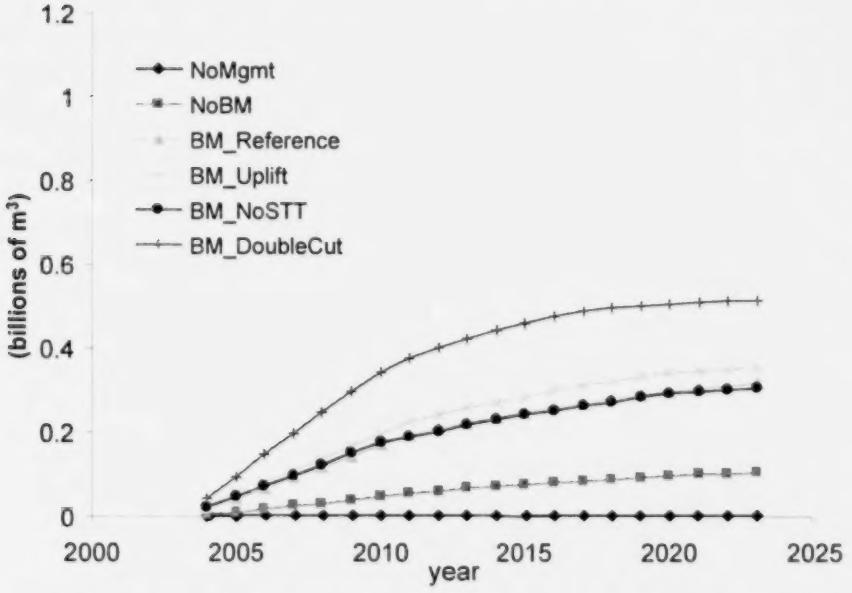

Figure 11. Comparison of projections of volume of green pine harvested among beetle management scenarios.

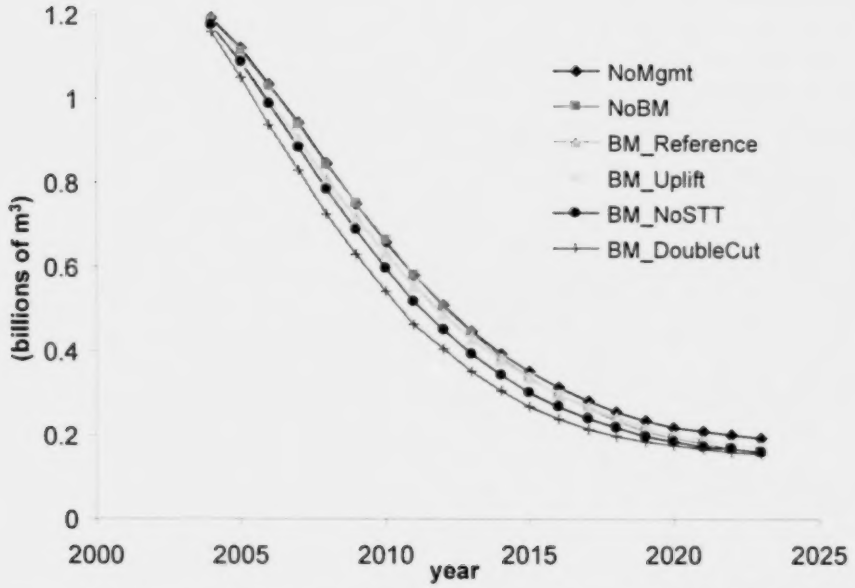

Figure 12. Comparison of projections of standing volume of pine on the THLB among beetle management scenarios.

4.5 Comparison of Salvage Focus Scenarios

As might be expected given the results reported in the previous section, focusing harvest on dead pine reduces non-recovered losses over the losses experienced in the reference scenario (Figure 13) where harvesting is focused on live pine at the leading edge of the outbreak. Focusing salvage on the highest volume of salvage available reduces losses more than focusing on the stands with the highest proportion of salvage (Figure 13). The reason is that stands with a high proportion of salvage do not necessarily contain a high volume of salvage. Focusing on any salvageable volume, rather than only stands with more than 50 m^3 of salvage, only makes a difference at the end of the simulation period when the remaining salvage is distributed throughout the landscape in relatively low volumes because of decay.

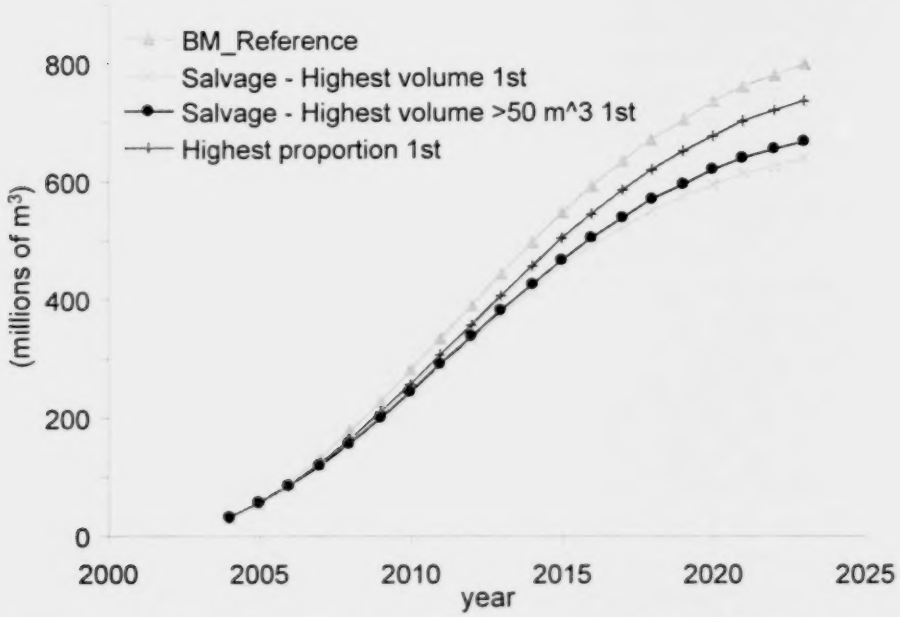

Figure 13. Comparison of cumulative non-recovered losses among salvage scenarios.

The reduction in non-recovered losses resulting from focusing harvest on salvage is not as great as one might expect or hope. In fact, losses are reduced by less than 25% from the reference scenario by the end of the simulation in the most optimistic salvage scenario (Figure 13). There are two reasons. First, there is a vast volume of dead pine to be harvested – on average throughout the projection period we estimate that there will be an average of approximately 200 million m^3 of dead pine volume on the landbase that could be salvaged. Given that the allowable annual cut for the interior of the province is 56 million m^3 (http://www.for.gov.bc.ca/hts/aac.htm) very high losses are to be expected regardless of the effort expended on salvage harvesting. Secondly, a large portion of the dead pine will be intermixed with green wood of other species (Table 4). As a result any harvesting targeted at salvage will also harvest green wood, thus reducing the efficiency of salvage at reducing non-recovered losses (unless harvesting techniques were applied to selectively harvest only standing dead pine).

As in the scenarios focusing on beetle management, the effect of salvage on non-recovered losses depends on the location in the province. For example, Figure 14 shows that, in Quesnel, focusing on the highest proportion of salvage results in more non-recovered losses than the reference scenario. The reason is that the forest in Quesnel is dominated by stands with a high proportion of pine (Table 4) and a relatively high proportion of that is already killed at the beginning of the simulation (25%). As a result the strategy forces some of the harvesting into

stands with high proportions killed, but low overall volumes (e.g. younger ages) whereas the reference scenario and the other salvage scenarios focus on stands with higher volumes of dead wood, regardless of the actual level of kill, which in this case forces harvesting in stands that tend to be older and with higher proportions killed. Note that in Quesnel none of the strategies result in much difference in non-recovered losses simply because of the very large quantity of dead and decaying pine that is present.

The result for Bulkley TSA (Figure 14) shows that, in the case of a management unit with relatively low levels beetle kill at the beginning of the simulation and relatively low amount of pine overall, focusing on salvage can have a much more significant effect on non-recovered losses over that experienced over the entire province.

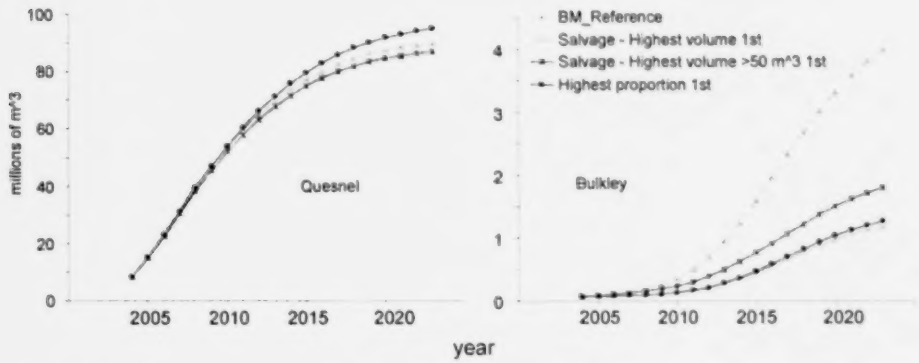

Figure 14. Comparison of cumulative non-recovered losses among salvage scenarios for the Quesnel and Bulkley TSAs

Figure 15 illustrates an unexpected result of the modeling of the salvage focus scenarios. That is, the salvage focus scenarios result in lower levels of kill by beetles than does the reference scenario in which "beetle management" is the focus. The reason is that the reference scenario focuses on newly attacked stands at the leading edge of the outbreak, regardless of the capacity of these stands to contribute to the outbreak. By focusing on salvage, stands with high levels of attack are targeted, often several years after the outbreak has grown in these stands when they are at the height of their capacity to produce beetles. That is, targeting the leading-edge attempts to reduce the *extent* of an outbreak. However, targeting high-attack stands behind the leading edge may correspond to an approach to reduce the *intensity* of an outbreak. We will adjust the behaviour of the beetle management scenarios during the next year's work to assess the importance of this finding.

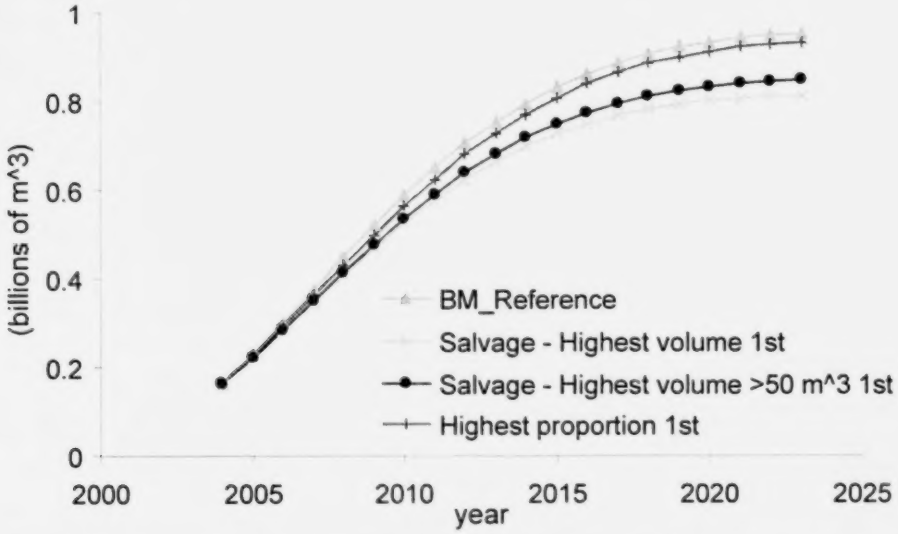

Figure 15. Comparison of cumulative volume killed by beetles among salvage scenarios

Our overall conclusion about the expected level of non-recovered losses is extremely sensitive to the annual rate of decay of useable dead pine volume (Figure 16). Losses a low as 10% per year have been reported for some areas on the Chilcotin Plateau with cold, dry climates (Taylor, pers. comm.). Feedback at a recent workshop on the modeling approach described here indicated that we should adopt a concept of "shelf life" for a given product (e.g. sawlogs, pulp, bio-fuels, etc.) rather than use a decay rate. It was suggested that "shelf life" is a step function in which there is no little or no loss of "utility" for some period of time and after that there is no "utility". It has been suggested that the shelf life for sawlogs may be a little as 2 years and a great as 10 years depending on climatic conditions. In the coming year we will endeavour to obtain the best possible shelf life estimates for modeling purposes

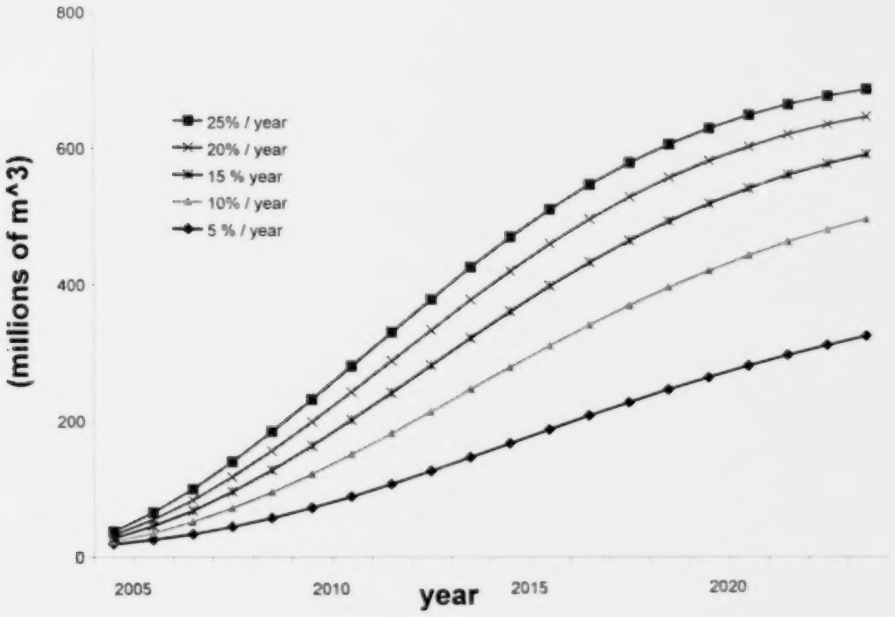

Figure 16. Sensitivity of projections of cumulative non-recovered losses to assumptions about annual rate of decay.

5.0 Conclusions and Next Steps

Our analysis of the current mountain pine beetle outbreak suggests that this outbreak is an order of magnitude larger, both in area infested and volume killed than any previous out break. The largest previous outbreak described by Wood and Unger (1996) was 650 000 hectares in size and occurred on the Chilcotin Plateau between 1930 and 1936. Our analysis indicates that it is most likely that the current outbreak will continue largely unabated until the majority of susceptible host stands in the province are affected. The model might be criticized because we do not include events such as unseasonably cold winter weather that might stop or slow the outbreak. It is true that by excluding the effect of unfavourable weather patterns, we are essentially projecting a worst-case scenario. However, we note that this outbreak is by now so widely distributed that there is not a high probability that the province will experience a severe cold weather event of sufficient to affect a significant proportion of the population (Spittlehouse pers. comm.). While there is a wide range of factors that affect mountain pine beetle population dynamics, the general understanding seems to be that once an outbreak has developed, it tends to proceed either until very cold weather causes massive beetle mortality, or until the supply of suitable hosts is depleted (Berryman et al. 1984; Samman and Logan 2000; Wood and Unger 1996). The only possible exception to this pattern appears to be the outbreak in the Flathead in 1977 to 1981 although observations about the collapse of this outbreak are equivocal (Young 1988). The results of this analysis are broadly consistent with conclusions from previous landscape scale-scale analyses in Kamloops, Williams Lake, Morice and Lakes (Fall et al. 2001; 2002; 2003a; 2003b).

The model results project that the peak of the outbreak will occur in 2007 or 2008 and the annual kill of pine volume, at that time, will be more than 70 million m^3 per year. We project that significant volumes (>30 million m^3) will continue to be killed until at least 2015. Further we project that pine mortality will not decrease to pre-outbreak levels until after 2020. We stress that these projections represent the worst possible case. It is conceivable that some unforeseen population stopping/slowing event may occur and/or that level of mortality within stands may not be as high as we project.

Our analysis indicates that single tree treatments, at currently funded levels, reduce the peak in annual kill but have little effect on total cumulative kill. We stress that this is a provincial scale conclusion. There is good evidence from both the provincial scale model and the district scale modeling done in Kamloops (Fall *et al.* 2001) that single tree treatments can be effective in protecting specific forest values under outbreak conditions that are less severe than those being experienced near the centre of current the infestation.

We examined scenarios that modeled a range of green tree harvesting directed at beetle management. Our fundamental conclusion is that, regardless of the

"effort" expended on beetle management, the standing volume of green pine at the end of the outbreak is approximately the same. The reason for this is that in order to manage beetles we harvest green pine. Increasing our efforts on beetle management results in a concomitant increase in the harvest of green pine. Further we found that focusing harvest on green-infested trees does not delay the timing of the peak in annual mortality of pine due to beetles. This demonstrates that, as modeled, beetle management does not slow the outbreak at a provincial scale. This result may not be applicable for any given management unit, particularly those at the periphery of the outbreak.

Our results indicate that focusing harvesting on salvage focus is not as effective at reducing non-recovered losses as we might hope or expect. Salvage strategies are only partially effective for two reasons: there will be a very large amount of decaying pine and it will be intermixed with live pine. Again we note that while this conclusion holds broadly over the whole province, there are some areas where salvage strategies seem much more effective. Where salvage operations are undertaken near the beginning of the outbreak and there is a relatively low volume of susceptible pine, our projections show that salvage focus management can have a very significant impact on mitigating non-recovered losses. There is some indication that focusing harvesting on salvage can be as effective, if not more effective, at managing the beetle outbreak than focusing harvesting on "green attack" is.

There are two major sources of uncertainty in our current results:

- We are uncertain about mountain pine beetle stopping conditions within a given stand. That is, although we are confident that our projection of timing and pattern are justified based on the overview data, we have some reservations regarding the actual final volumes killed within each stand. This is partially due to the lack of empirical experience with declining epidemics. We suspect that our estimates of volume killed within any given stand may be too high (but not likely by more than 20%). We also have some uncertainty about the rates at which the infestation begins in areas outside the currently infested area (i.e. more mountainous and fragmented habitat than is seen on the interior plateau).
- We are uncertain about ecological and economic decay rates. We applied a rate of 20%/year. Clearly this would vary across diverse site and climatic conditions in the province. We expect that the rate applied may be on the high side, both in terms of the magnitude (which may be high for drier areas of the province) and because no delay was considered (i.e. volume may not begin to degrade for several years post-mortality). Economic decay also depends on the target products, which we did not consider (e.g. trees targeted as sawlogs may experience more rapid economic decay than trees targeted as pulp).

Hence, the first issue suggests that total volumes killed may be somewhat less than reported here, while the second issue suggests that volume recovered may be somewhat higher (and NRL somewhat lower) that reported.

Both of these issues will form a central focus for refinement and exploration in the upcoming year. Our other tasks will be to refine how BMU types are established, understand some odd behavior in specific management units, and improve the indicator file format. We will also assess some other management scenarios, such as using a volume-based AAC (vs. the area-based AAC reported herein) and improving salvage-focus harvesting and how policies for uplifts may differ from the base AAC.

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Appendix 1

Spatial Metadata
http://www.for.gov.bc.ca/hre/bcmpb/BCMPB_Appendix1_SpatialMetadata.pdf

Appendix 2

Management Sub-model Details
http://www.for.gov.bc.ca/hre/bcmpb/BCMPB_Appendix2_ManagementModel.pdf

Appendix 3

MPB Sub-model Details
http://www.for.gov.bc.ca/hre/bcmpb/BCMPB_Appendix3_MPBProjectionModel.pdf

Appendix 4

Indicator Files
http://www.for.gov.bc.ca/hre/bcmpb/BCMPB_Appendix4_IndicatorFileDescriptions.pdf

Appendix 5

Verification and Sensitivity of the Beetle Projection Sub-Model
http://www.for.gov.bc.ca/hre/bcmpb/BCMPB_Appendix5_BeetleModelVerification.pdf

Provincial-Level Projection of the Current Mountain Pine Beetle Outbreak:

An Overview of the Model (BCMPB) and Draft Results of Year 1 of the Project

Appendix 1: Spatial Metadata

Supported by the
Mountain Pine Beetle Initiative of the Canadian Forest Service
and the BC Forest Service

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Marvin Eng, Research Branch, BC Min. of Forests

April 2004

Purpose of the document

This document specifies the spatial data used by the BCMPB (Provincial Scale Mountain Pine Beetle Projection Model). It also describes in some detail the methods used to generate the spatial data. The document is not intended to provide enough detail to completely reproduce the data. Rather we intend that this appendix could provide enough information for a well informed reader to gain some understanding about how the data was compiled.

Spatial layers used by the model

Table 1 lists all of the spatial data used by the model. The layers are divided into 5 types:

1. Beetle related information is used to initiate the beetle projection model. All of the layers used by the model are, in fact, calculated from other information, primarily the annual severity of attack data extracted from the provincial aerial overview data. The method of extracting that information is described in the section titled Beetle Population Data.
2. Initiation layers represent the non-recovered losses experience to 2002 and 2003 as a result of the infestation from 1999. Those layers are used to "initiate" the NRLs at the correct level.
3. Forest Cover data was obtained from two separate sources as described in the section titled Forest Cover Data.
4. Management consists of that information required by the forest management submodel. It is data that is used to either direct or constrain harvesting and single tree treatments.
5. Reporting Strata are required to develop the indicator files. Reporting strata do not influence the behaviour of the model. Rather they are used in a post-processing step to "cut" the results by areas of interest to specific clients.

Additional metadata for the spatial layers used by the model and for layers used to create the layers used by the model can be found in http://www.for.gov.bc.ca/hre/bcmpb/BCMPB_SpatialMetadata.xls.

Table 1. Spatial layers used by the model (BCMPB).

Layer Name	Layer Description	Layer Type	Calculated
habitatCo	Beetle habitat	Beetle	Yes
svCombine02	combined severity in 2002	Beetle	Yes
svCombine03	combined severity in 2003	Beetle	Yes
cumPressure3	Cummulative beetle pressure in 2002	Beetle	Yes
cumPressure4	Cummulative beetle pressure in 2003	Beetle	Yes
cumKill02	Cummulative percentage of pine killed in 2002	Beetle	Yes
cumKill03	Cummulative percentage of pine killed in 2003	Beetle	Yes
localPressure3	local beetle pressure 2002	Beetle	Yes

localPressure4	local beetle pressure 2003	Beetle	Yes
timeSinceKill02	Time since the last beetle kill in 2002	Beetle	Yes
timeSinceKill03	Time since the last beetle kill in 2003	Beetle	Yes
nrl02	Non recovered losses in 2002	Initiation	Yes
nrl03	Non recovered losses in 2003	Initiation	Yes
pcpClassCo	Percent pine classified	Forest Cover	Yes
ageCo	age of the forest	Forest Cover	No
itg_b	Inventory type groups	Forest Cover	No
pcpCo	Percent pine	Forest Cover	No
spc_pine_b	Pine species	Forest Cover	No
sindex_b	Site index	Forest Cover	No
vol_b	Total timber volume	Forest Cover	No
volpine_b	Volume of pine	Forest Cover	No
Dist2Road	Distance to roads	Management	Yes
NearestRoadLoc	Location of the nearest road	Management	Yes
bmu03	Beetle management unit designation in 2003	Management	No
bmuname	Beetle Management unit id by name	Management	No
dem	Digital elevation model	Management	No
ebbma03	Emergency bark beetle management area designations in 2003	Management	No
mgmtunits	Forest management units (TSAs and TFLs)	Management	No
thlbtrue	Timber harvesting landbase	Management	No
vqo	Visual quality objectives	Management	No
rmz2	Generalized Resource management zones	Reporting Strata	Yes
abec_bc	Biogeoclimatic subzone variants	Reporting Strata	No
cariherd	Caribou herds	Reporting Strata	No
gbearpopn	Grizzly bear populations	Reporting Strata	No
lu	Landscape Planning Units	Reporting Strata	No
spupl	Pine seed planning units	Reporting Strata	No
parks	Provincial and National Parks	Reporting Strata	No
provtrue	Provincial land mass	Reporting Strata	No
rmz	Resource management zones	Reporting Strata	No
spusx	Spruce seed planning units	Reporting Strata	No

Beetle Population Data

The annual kill for each year from 1999 to 2003 was obtained from the Provincial Aerial Overview ("the overview") data. The method involved overlaying a 1200 meter grid on the polygonal and spot data from the overview. The area affected in each grid cell was then calculated as the area in a severity class multiplied by the mid-point of the kill estimate for that severity class. For the spot data the area of the spot was used. The following rather crude ARC/INFO macro shows how the calculations were performed for one year of the overview data. A description of how the 1200 meter grid data was converted to a 400 meter grids is provided in Appendix 3.

```
/* Rather Crude AML Author Marvin Eng
/* Create overlay of fishnet and points and polygon data
/* and summary tables of points and polygon data
Precision Double Highest
&echo &brief

/* point overlay
 Identity C:\Work\mpb\indata\mofairoverdataraw\prvspot03
C:\Work\mpb\indata\mpbpopn\fishnet C:\Work\MPB\InData\MPBPopn\spot03 Point #
Join

/* point statistics
Statistics C:\Work\mpb\indata\mpbpopn\spot03.pat
C:\Work\MPB\InData\MPBPopn\spot03.freq fishnet#
Sum NUM_TREES
Sum spot_area
end

/* point output
infodbase spot03.freq spot03

/* polygon overlays and calculations
Identity C:\Work\mpb\indata\mofairoverdataraw\prvpoly03
C:\Work\mpb\indata\mpbpopn\fishnet C:\Work\MPB\InData\MPBPopn\poly03 Poly
0.000001 Join
additem poly03.pat poly03.pat perckill 4 4 f 2
additem poly03.pat poly03.pat areakill 8 18 f 5
tables
        select poly03.pat
        reselect severity = 'L'
        calc perckill = 0.05
        select poly03.pat
        reselect severity = 'M'
        calc perckill = 0.20
        select poly03.pat
        reselect severity = 'S'
```

```
        calc perckill = 0.50
        select poly03.pat
        reselect severity = 'V'
        calc perckill = 0.50

        select poly03.pat
        calc areakill = area * perckill
quit


/* polygon statistics
STATISTICS C:\Work\mpb\indata\mpbpopn\poly03.pat
C:\Work\MPB\InData\MPBPopn\poly03.freq FISHNET#
Sum AREA
Sum PERCKILL
Sum AREAKILL
end


/* polygon output
infodbase poly03.freq poly03

/* gets the area killed into an attribute in fishnet.  adds poly and spot area
/* add area killed attribute
/* This is the second time around so we don't need to add additem fishnet.pat fishnet.pat
areakill03 8 18 f 5

/* create indices for more rapid calculations
indexitem fishnet.pat fishnet#

indexitem poly03.freq fishnet#
indexitem spot03.freq fishnet#
/*  Create relates
relate add rpoly03 poly03.freq info fishnet# fishnet# linear ro
relate add rspot03 spot03.freq info fishnet# fishnet# linear ro
/* Do calculations sum-spot_area is in ha so is multipled by 5000 to give 50% attack in
meters squared
/* this give equivalent units to sum-areakill
tables
select fishnet.pat
 calc areakill03 = 0
 calc areakill03 = rpoly03//sum-areakill
 calc areakill03 = areakill03 + ( rspot03//sum-spot_area * 5000 )
quit
```

Forest Cover Data

All of the forest cover data used in the model was obtained from two separate sources. The majority of the data, for all area managed as Timber Supply Areas was obtained from the provincial "corporate" spatial database known as the Land and Resource Data Warehouse (LRDW). The methods of obtaining the information and converting it to 400 meter grids are described below. For some areas of the province the LRDW does not contain any data. These primarily are:

- large areas of private land on Vancouver Island and the in the southern east Kootenays;
- most Tree Farm Licenses (TFLs); and
- some large parks created prior to the advent of digital forest cover mapping.

Data for the parks was made available as a result of the work done on the 1994 Forest and Range Recreation Resource Analysis. The authors obtained the 1956 continuous forest cover mapping for the missing parks. The information was digitized, the labels were converted to modern formats and the data on age and volume was projected to the current date. Some updates for major depletions were incorporated through visual interpretation of satellite imagery. Data for TFLs was obtained by the Crown in 1996 as part of a project that was designed to complete the forest cover mapping for the province. Unfortunately there is no available source of forest cover data for the private land. The TFL and Parks data was incorporated into

The LRDW Forest Cover data were extracted in 1:250,000 NTS map sheet "blocks" from the Ministry of Sustainable Resource Management's Land and Resource Data Warehouse using Arc/Info. Each of the resulting 1:250,000 Arc/Info "Coverages" were populated with the forest stand information required for this study. Percent Pine and Pine Species were also calculated for each forest stand. Coverages containing only a single forest inventory theme were created (e.g. stand age) for each map sheet. This was done so that the coverages reflected the spatial distribution the inventory theme rather than the spatial distribution of the stands. Each 1:250,000 forest inventory theme coverage was converted to an Arc/Info raster "Grid" using a raster resolution of 400 m by 400 m. For each forest inventory theme, the 1:250,000 raster grids were joined together to create a single raster grid which covered the entire province. Each province-wide grid was converted to Arc/Info ASCII format for subsequent use in SELES.

A similar process was used to extract the data for TFLs and Parks from the "continuous forest cover dataset". The two datasets were then combined such that if LRDW data was available it was used otherwise the continuous forest cover data was used.

Management (forest) data

The following management data layers were obtained directly from their sources and simply converted to a 400 meter grid

- bmu03
- bmuname

- dem
- ebbma03
- mgmtunits
- vqo

The road related layers (Dist2Road and NearestRoadLoc) were calculated based on the location of roads as represented in the LRDW. Any road related feature code was used to indicate the presence of a road.

Development of a spatially explicit timber harvesting landbase (THLB) (thlbtrue) for the entire province was a non-trivial task. There were 3 principal problems:

1. A large quantity of data in varying formats had to be processed;
2. All the expressions of percent inclusion in the THLB had to be converted to 100% in or 100% out of the THLB; and
3. THLB for the Tree Farm Licenses is not readily available and had to be estimated.

The initial input data was provided primarily as district files either in ARC coverage (vector) and ARC grid (raster) format. Depending on the area, in some instances there was areas of overlap between data sets. One or more attributes relating to the THLB were present in all the data sets and all data sets had a attribute that contained the THLB inclusion factor (in percent). It is this attribute that was used to create the provincial THLB grid. Most, but not all of the data sets have an attribute that classified the THLB by type of inclusion where:

- "X" = outside THLB
- "N" = within THLB but zero percent inclusion
- "P" = partial inclusion in THLB
- "C" = one hundred percent inclusion in THLB

Since only the percentage of inclusion within the THLB was of interest, the above inclusion classification was not retained in the final provincial (THLB_BC) data set.

The procedure for creating the THLB grid from the input data is outlined below:

1. If the data set was in ARC coverage format, the dataset all items except those relating to the THLB were dropped, sliver polygons were removed if necessary and the coverage was dissolved with the #ALL option in ARC. In some cases this 'clean-up' greatly reduced the size of the dataset.
2. Coverages were converted to GRID with a 50 metre x 50 metre cell size using the POLYGRID command in Arc.
3. Depending on the original data set, areas with an inclusion factor value of zero OR a 'no-data' could be either: a) areas outside the THLB, b)areas within the THLB but with a zero inclusion factor or c) areas outside the spatial extent of the original coverage. All 'no data' areas of each GRID were converted to zero using the CON and ISNULL commands in GRID. This was done to ensure all areas within the BLOCKMEAN processing window were used in the computation. This provided consistency with how each dataset was processed (as zero and no data values could mean the same or different things)

and to prevent overestimating the percentage of THLB inclusion which occurs when areas with 0 percent inclusion have a 'no-data' value (as they are then excluded from determining the mean value in BLOCKMEAN).

4. Each 50 metre grid was aggregated into a grid with a 400 metre by 400 metre cell size using the BLOCKMEAN GRID function. Since all ISNULL areas were previously converted to zero, all 50 metre cells within the processing window were used in determining the mean value.
5. All areas with zero value were converted to ISNULL in preparation of the appending process whereby the single grids were appended together to create a provincial dataset. This was done so that where areas of overlap occurred, areas with a zero value from one grid (representing areas outside the original coverage area) did not 'erase' the overlapping areas of another grid during the append process where the inclusion factor was greater than zero
6. The analysis environment was set to a provincial extent. Xmin ymin xmax ymax values were as follows: 270000 330000 1874400 1736400. All individual grids were then appended together to create the final provincial dataset of THLB inclusion. Since the order of input determines the priority in areas of overlap in cases of overlap, those data sets seen as more accurate were appended first. THLB_BC is the final output (400m x 400m, floating point type).

The resulting grid contained a "percent inclusion" in the THLB that was a continuous value from 0 to 1. We converted that to only 0 or 1 by randomly including cells in the THLB based on the percentage inclusion.

The area within a Tree Farm License was place in the THLB if it met all of the following criteria:

- Forested
- Site Index greater than 7
- Not deciduous
- Slope less than 40%
- Elevation less than 1800 meters.

Subsequently an additional 2.5% of the cells in each TFL were removed from the THLB

Reporting strata

The spatial layers for the reporting strata were obtained directly from the LRDW and simply converted to 400 meter grids.

DRAFT

Provincial-Level Projection of the Current Mountain Pine Beetle Outbreak:

An Overview of the Model (BCMPB) and Draft Results of Year 1 of the Project

Appendix 2. Management Sub-model Details

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Andrew Fall, Gowlland Technologies Ltd.

April 2004

The management sub-models include planning, single-tree treatment and harvesting components. The broad objectives of these components are to capture the interaction between human forest management planning and actions, with feedbacks between the forest state, the MPB state and forest management constraints and goals (see Figure 1 in main summary document).

A2.1 Planning: Inventory Availability

This event performs an inventory analysis each time step. Unlike in a timber supply model, volume/ha is not updated by the model, but is rather an input grid. That is, the model tracks depletion of growing stock from harvesting and MPB, but not accrual of new volume due to stand aging. Given the short time horizon of model runs, this helps reduce model complexity.

We define *merchantable* stands as those with at least 150 m3/ha. We define *available* stands as merchantable stands that are within 2km of road access, and in zones not exceeding amount of young to meet visual quality objectives. The visual quality constraints applied are shown in Table 1, and were met within each landscape unit. These were estimated from values used in some TSAs, but we plan on assessing sensitivity of results to these values in the upcoming year.

Table 1. Visual quality objectives applied by BCMPB

VQO Type	Young age	Max. young
IRM	25 years	25%
Maximum Modification	25 years	25%
Modification	25 years	20%
Partial Retention	25 years	15%
Retention	25 years	5%
Preservation	25 years	1%

A2.2 Planning: BMU rating

The second key task of this sub-model is to establish beetle management unit (BMU) types: monitor, suppression, holding action or salvage. For each BMU, an "outbreak level index" (*BMU rating)* was computed as follows:

Area with endemic MPB state / area with MPB > endemic state

The index is first computed for each BMU separately. Then the list of BMUs is sorted according to the index, with largest values first. BMUs are then processed sequentially in this order. BMUs with no detectable MPB are processed first and assigned a *monitor* type. If the single-tree budget (after reductions for previously processed BMUs) is capable of addressing at least 80% of the spots, then a BMU is assigned a *suppression* type. Otherwise, if the BMU rating is ≥ 0.2 (i.e. at most 80% of the attack is in higher MPB attack states) and the total area attacked in the BMU is less than 5,000 ha, then the BMU is assigned a *holding action* type. Finally, unassigned BMUs are assigned a *salvage* type.

A2.3 Operations: Harvesting

This event performs forest harvesting in some portion of available cells. It applies target AACs simultaneously in each TSA/TFL in the province. Each management unit is processed independently, and so the model can be described from the perspective of a single unit. Currently the harvest target for each management unit is specified using an area-based AAC as the number of hectares to harvest within the THLB (Table 2). The model is capable of applying the harvest target as a volume-based AAC, and this will be explored in the upcoming project year.

Table 2. Harvest levels for each management unit applied by BCMPB up to year 2013, specified as an annual area (ha) to harvest.

MgmtUnit	2003	2004	2005	2006	2007	2008	2009	2010	2011	2012	2013
100MileHouse	4371	4371	4371	4371	4371	4371	4371	5352	5352	5352	5352
Arrow	1829	1829	1829	1829	1829	1829	1829	1882	1882	1882	1882
Arrowsmith	521	521	521	521	571	571	571	571	571	513	513
Boundary	2594	2594	2594	2594	2594	2594	2594	2821	2821	2821	2821
Bulkley	3099	3099	3099	3099	3099	3099	3099	2756	2756	2756	2756
Cassiar	1325	1325	1325	1325	1325	1325	1325	1325	1288	1288	1288
Cranberry	246	246	246	246	252	252	252	252	252	252	252
Cranbrook	3609	3609	3609	3609	3609	3609	4068	4068	4068	4068	4068
DawsonCreek	7459	7459	7459	7459	7459	7459	7459	7459	7459	6867	6867
FortNelson	6842	6842	6842	6842	6842	6842	7141	7141	7141	7141	7141
FtStJohn	11426	11426	11426	11426	11426	11426	11426	11426	11426	11449	11449
Fraser	2779	2779	2779	2779	2779	2779	2989	2989	2989	2989	2989
Golden	1393	1393	1393	1393	1393	1500	1500	1500	1500	1500	1500
Invermere	2291	2291	2291	2291	2291	2291	2291	2291	2396	2396	2396
Kalum	783	783	783	783	783	783	818	818	818	818	818
Kamloops	8050	8050	8050	8050	8050	8050	8050	7885	7885	7885	7885
Kingcome	2189	2189	2189	2189	2189	2189	2020	2020	2020	2020	2020
Kispiox	2349	2349	2349	2349	2349	2349	2349	2349	2516	2516	2516
KootenayLake	2596	2596	2596	2596	2596	2596	2680	2680	2680	2680	2680
Lakes	4698	4698	4698	4698	4698	4698	4698	4442	4442	4442	4442
Lillooet	2858	2858	2858	2858	2858	2858	2970	2970	2970	2970	2970
Mackenzie	9478	9478	9478	9478	9478	9478	9478	9478	9730	9730	9730
Merritt	5366	5366	5366	5366	5366	5366	5366	5366	5128	5128	5128
MidCoast	1631	1631	1633	1633	1633	1633	1633	1751	1751	1751	1751
Morice	7000	7000	7000	7000	7000	7000	7000	7000	7000	7500	7500
Nass	1818	1818	1818	1818	1818	1818	1818	1678	1678	1678	1678
NorthCoast	775	775	775	775	775	775	925	925	925	925	925
Okanagan	7805	7805	7805	7805	7805	7805	8786	8786	8786	8786	8786
PrinceGeorge	29000	29000	29000	29000	29000	29000	29000	29000	29000	27000	27000
QueenCharlotte	581	581	581	638	638	638	638	638	620	620	620
Quesnel	9542	9542	9542	9542	9542	9542	9542	10019	10019	10019	10019
Revelstoke	468	468	468	468	468	468	495	495	495	495	495
RobsonValley	1750	1750	1750	1750	1750	1750	1750	1720	1720	1720	1720
Soo	761	761	761	761	761	761	804	804	804	804	804
Strathcona	2077	2077	2077	2077	2077	2077	2077	1761	1761	1761	1761
SunshineCoast	1715	1715	1715	1715	1694	1694	1694	1694	1694	1670	1670

WilliamsLake	27835	27835	27835	27835	27835	27835	27835	13741	13741	13741	13741
TFL1	1300	1300	1300	1300	1300	1300	1300	1300	1300	1300	1300
TFL10	243	243	243	243	243	243	243	243	243	243	243
TFL14	675	675	675	675	675	675	675	675	675	675	675
TFL15	361	361	361	361	361	361	361	361	361	361	361
TFL18	571	571	571	571	571	571	571	571	571	571	571
TFL19	1541	1541	1541	1541	1541	1541	1541	1541	1541	1541	1541
TFL23	1863	1863	1863	1863	1863	1863	1863	1863	1863	1863	1863
TFL25	2362	2362	2362	2362	2362	2362	2362	2362	2362	2362	2362
TFL26	593	593	593	593	593	593	593	593	593	593	593
TFL3	261	261	261	261	261	261	261	261	261	261	261
TFL30	1096	1096	1096	1096	1096	1096	1096	1096	1096	1096	1096
TFL33	67	67	67	67	67	67	67	67	67	67	67
TFL35	442	442	442	442	442	442	442	442	442	442	442
TFL37	1307	1307	1307	1307	1307	1307	1307	1307	1307	1307	1307
TFL38	485	485	485	485	485	485	485	485	485	485	485
TFL39	901	901	901	901	901	901	901	901	901	901	901
TFL41	559	559	559	559	559	559	559	559	559	559	559
TFL42	561	561	561	561	561	561	561	561	561	561	561
TFL43	156	156	156	156	156	156	156	156	156	156	156
TFL44	5886	5886	5886	5886	5886	5886	5886	5886	5886	5886	5886
TFL45	356	356	356	356	356	356	356	356	356	356	356
TFL46	775	775	775	775	775	775	775	775	775	775	775
TFL47	1313	1313	1313	1313	1313	1313	1313	1313	1313	1313	1313
TFL48	2447	2447	2447	2447	2447	2447	2447	2447	2447	2447	2447
TFL49	1539	1539	1539	1539	1539	1539	1539	1539	1539	1539	1539
TFL5	829	829	829	829	829	829	829	829	829	829	829
TFL52	1738	1738	1738	1738	1738	1738	1738	1738	1738	1738	1738
TFL53	1623	1623	1623	1623	1623	1623	1623	1623	1623	1623	1623
TFL54	2750	2750	2750	2750	2750	2750	2750	2750	2750	2750	2750
TFL55	207	207	207	207	207	207	207	207	207	207	207
TFL56	199	199	199	199	199	199	199	199	199	199	199
TFL57	123	123	123	123	123	123	123	123	123	123	123
TFL6	988	988	988	988	988	988	988	988	988	988	988
TFL8	709	709	709	709	709	709	709	709	709	709	709

Each model year, the target AAC provides a "beetle management potential". How this is allocated across a unit depends on the BMU ratings, MPB state, stand ages/volumes and salvage volumes. The available cells in the unit are stratified into groups based on BMU rating and MPB outbreak state, and processed according to a priority order. The following described the strata, from highest to lowest priority within a management unit:

- Low and moderate MPB in suppression BMUs: focuses harvesting on leading edge attack.
- Endemic and severe MPB in suppression BMUs: focuses harvesting on other MPB attack in suppression BMUs.
- Low and moderate MPB in holding action BMUs: focuses harvesting on leading edge attack

- Severe MPB in holding action BMUs: focuses harvesting on high populations
- Salvage in salvage BMUs: areas with adequate salvage (> 50m^3/ha)
- Moderate and severe MPB in salvage BMUs: focuses harvesting on areas likely to result in substantial salvage
- Salvage in other BMUs, and low and endemic MPB in salvage BMUs: remaining "mop-up" classes
- Green harvest (no MPB) in any BMU: regular green harvest

All available cells within a stratum are harvested before any cells in subsequent strata. Within each stratum, ordering is according to stand age (linearly increase with age), distance to roads (linear decline with distance) or salvagable volume (linear increase with volume or proportion), depending on BMU type and scenario parameters. In units with no MPB (i.e. all BMUs are *monitor* types), harvesting will be "green harvest", and hence according to "oldest-first, nearest to road". In management units with a mixture of BMU types and MPB states, the actual allocation of harvesting will primarily focus on reducing populations (i.e. using MPB state), followed by salvage. In management units dominated by salvage BMU types, harvesting will be "highest salvage-volume first, nearest to road".

The default cutblock size was up to 16-32ha (1-2 cells), based on a spatial assessment of recent block sizes in different regions of the province, and on the bark beetle regulations. Blocks are placed sequentially within a management unit until the harvest target is met.

Where blocks are placed, volume (green and salvage) is recuperated, harvest indicators are updated, MPB state is reset to "no MPB" (i.e. the model assumes close to 100% efficacy), stand age is reset to 0, and visual targets are updated. In addition, this sub-model explicitly connects cutblocks to the main road network by adding a link from the first cell harvested in a block to the nearest existing road. It then updates a map indicating the distance from each cell to the nearest existing road. This step permits estimation of the amount of road constructed under a given management regime, and to determine accessibility in the future.

A2.4 Operations: Single-Tree Treatments

This sub-model simulates fell and burn and MSMA treatment methods in each *suppression* BMU of the province simultaneously. First the provincial budget is allocated among *suppression* BMUs proportionally based on level of endemic MPB state. That is, if a suppression BMU has x% of the total endemic cells of all suppression BMUs, then it will receive x% of the single-tree treatment budget. Given a single-tree treatment allocation, the remainder of the model description can be cast from the perspective of a single BMU. Single-tree treatments are generally applied in inaccessible areas (up to 5km from a road) or areas with low (endemic and some low MPB state) beetle populations. These treatments are applied to individual cells, and the volume is not recovered. The model assumes

that the MPB state is reduced by one level (i.e. endemic state becomes "no MBP", while low becomes endemic).

Provincial-Level Projection of the Current Mountain Pine Beetle Outbreak:

An

Overview of the Model (BCMPB)

and

Draft Results of Year 1 of the Project

Appendix 3. Mountain Pine Beetle Projection

Supported by the

Mountain Pine Beetle Initiative of the Canadian Forest Service

and the BC Forest Service

Canada

BRITISH COLUMBIA

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1 Data Preparation Steps

1.1 Get age and percent pine from forest cover database

Spatial layers representing forest age in years and percentage of the volume of timber that is contributed by pine (of any species) were extracted from the provincial digital forest cover map, also known as the Land and Resource Data Warehouse (http://srmgww.bcgov/bisd/imb/ds/projects/idw/index.html). Only data available in the LRDW was used to parameterize the beetle model. There is no data in the LRDW for Tree Farm Licenses and some of the large old parks. Forest cover data are available for these areas, and was used when model projections were made, but the quality and currency of this data is not suitable for creating parameter estimates.

Forest age is available directly as a field in the LRDW database. The percentage of pine was determined by identifying which, if any, of the six species in the database were some species of pine and then summing the associated species percent fields for those species. In general, only one pine species was present in a stand although there were a surprising number of exceptions to this rule.

The resulting information was extracted as ARC/INFO polygon coverages and generalized on age and percent pine. The coverages were then converted to grids with a 16 hectare cell size using the ARC POLYGRID command. This command works by intersecting the polygon layer with a 16 hectare grid and determining attribute of the largest resulting polygon for each grid cell. The entire grid cell is then assigned that attribute

1.2 Classify habitat types

We constrain beetles to occur only in areas of suitable climate with some pine component. The pine must also be greater than 60 years old, but stand age is a dynamic layer in our projection model, so we include this factor as a separate constraint, rather

than recalculating the habitat suitability map each year. Thus, we classify each 400-metre cell into one of 6 suitability types according to the following scheme:

If no forest cover data is available (TFL's and Parks), then:

Suitability Type = **No Data**

Otherwise, if data indicates no forest cover (age or percent pine value of –1, indicating lakes, rocks, ice, etc), then:

Suitability Type = **No Forest**

Otherwise, if climate is unsuitable, and percent pine is greater than 0, then:

Suitability Type = Unsuitable Climate, With Pine

Otherwise, if climate is unsuitable, then:

Suitability Type = Unsuitable Climate, No Pine

Otherwise, if there is no pine present, then:

Suitability Type = **Suitable Climate, No Pine**

Otherwise, forest is suitable for beetles:

Suitability Type = **Suitable**

We define climatic suitability broadly by biogeoclimatic zone. Areas within the following biogeoclimatic zones are considered suitable:

- BG, ESSF, ICH, IDF, MS, PP, SBPS, SBS

For reference, zones deemed unsuitable are:

- AT, BWBS, CDF, CWH, MH, SWB

We further classify suitable habitat into discrete age and percent pine classes. We begin with 20-year age classes, running from 80 (61-80 years) through to 240 (>220 years). Percent pine is classified into 25 percent intervals – the 1-25% class includes areas with 1-25 percent pine, and so on. We separate areas labeled as 100% pine into a class of their own, in part because so much of the landscape falls into this one category, and in part because areas of 100% pine appear to be less heavily infested by beetles that areas which are 76-99% pine. This result is counter to out expectation, and we wish to retain a distinct 100% infestation class in order to check later whether the lower infestation rate in these stands remains when other factors are taken into account.

When classifying age and percent pine, there are a number of issues for us to consider. First, and most minimally, the amount of forest in each class must be large enough that we can reasonably assume the probabilities we observe are not just an artifact of small sample sizes. Beyond this, we must keep in mind that categories will be further divided by other factors including infestation history and the number of beetles in neighboring regions. With so many important factors, and so many possible categories of each factor, we run a significant risk of over specifying this model. In general, we should retain the minimum possible number of categories at each stage of model development.

1.3 Assign beetle infested area to suitable habitat

If we accept the unprocessed aerial overview survey at face value, we find that it is not uncommon for beetles to occur in unsuitable areas, including lakes and rivers well as forested area without pine. It is also common for the percentage of trees infested in a stand to be greater than the percentage of trees that are pine in that stand. Both these

situations are impossible, and so indicate errors in either the forest cover data or the beetle mapping. No doubt both data sets contain significant errors, but it is our view that the forest cover database is more reliable than the aerial overview survey data, so we assume that beetles mapped in unsuitable areas indicate an error in the survey data, not in our assessment of habitat suitability.

There are three main types of errors that may occur in the beetle survey data:

- The infestation extent and the number of trees killed within that extent may be correct, but the spatial location may be wrong. We expect this occurs most often when observers are mapping small beetle spots, where it is easy to see that beetles have killed a few trees in a small area, but also easy to get the location of this area slightly wrong. In this case, the beetles mapped do exist, but actually belong in nearby susceptible habitat.
- The infestation extent may be wrong. We expect this occurs when mappers are marking large infestations, and might not bother to omit unsuitable forest areas from the larger polygon. In this case, the beetles mapped are not in the wrong location, but simply do no exist, and should be omitted.
- The percentage of trees killed within an infested area may be wrong. We suspect that the percentage killed is the least reliable aspect of the aerial survey data. In part this is because it is easier to see red trees than green ones, and partly because humans are notoriously poor at assessing the quantitative values by eye. In this case, the infestation is in the right place, but the number of beetles is wrong.

Of course, while we can recognize that three types of errors may occur, we cannot to easily distinguish which type of error has occurred in a particular case, or how to remedy it. That said, we do think that some further processing of the aerial overview survey data will render this data more meaningful and useful.

To begin, we assume that the mapped location of an infestation may be up to 600 metres away from where the actual infestation occurred. In any 144 ha area the number of trees infested by beetles will be approximately right, but the data is uninformative about where exactly the infestation occurred within that area. Thus, we begin by laying a 1200 metre

by 1200 metre grid over the aerial survey polygon data, and summing the amount of beetle kill within each grid cell.

We then lay this 1200 metre beetle coverage over our more finely resolved (400 metre grid) forest cover information. Before continuing, we consider areas where no forest cover data is available (Suitability Type = No Data). Since we have no forest cover data for these areas, we cannot say whether beetles may occur there or not. We begin by erasing the beetles that fall within these No Data areas.

Within each 1200 by 1200 metre area, we assign remaining beetles to suitable habitat if there is any. We assume that no more trees can be infested than there are susceptible pine trees to infest, so the maximum area infested in any forest cell is equal to the percentage of pine. Subject to this constraint, I assign the area infested in each 1200 metre cluster equally among all suitable cells within that cluster. Thus, the infested area assigned to each suitable 400-metre cell is:

$$\text{AreaKilled}_{400} = \text{Min}\left(\frac{\text{AreaKilled}_{1200}}{\text{Number of Suitable Cells}}, \frac{\text{CellArea} * \text{PercentPine}}{100}\right) \quad \text{Eq. 1}$$

where AreaKilled_{1200} is the total area infested in the 1200 metre cluster, CellArea is the area of the 400-metre cell (160,000 m^2).

Once we have assigned infested area to the suitable habitat available, we are often left with beetles that we have no place to put. Assuming that locations designated unsuitable for beetles really are (i.e. the forest cover data is right), we determine that these beetles could not really have existed, and omit them from further analysis. For interest sake, we track the proportion of these beetles that fall into each (Figure 1). Overall, the amount of infested area that cannot be assigned to suitable habitat ranges from 13 to 17% over the whole province, depending on the year in question.

1.4 Classify infestation intensity

Having allocated the area infested by beetles among suitable areas, we assign the infestation at each location to one of 5 broad severity classes:

	Lower	"Mid"	Upper
Severe	**0.3**	**0.5**	**1**
Moderate	**0.1**	**0.2**	**0.299999**
Low	**0.01**	**0.05**	**0.099999**
Endemic	**0.000001**	**0.005**	**0.009999**
None	**0**	**0**	**0**

Table 1: Proportion of pine affected by beetles according to the aerial overview survey data.

Note that we are concerned with the proportion of pine area that is affected, rather than the proportion of total area. Thus, a cell where 10% of area is infested by beetles that contains only 10% pine will be considered severely affected. This differs from the severity ratings used in the aerial overview survey, which depend on the overall proportion of all trees that are infested.

1.5 What does "severe" really mean?

We observe that 25% of cells that are severely infested in 1999 to remain severely each year through to 2002. 42% of the cells severely infested in 2000 remain severely infested in 2002. According the classification above, more than 30% of susceptible pine is killed in one year of a "severe" infestation. If we accept a mid-value for severe of 50% kill, we effectively claim that up to 200% of susceptible pine has been killed in many areas over the period from 1999 to 2002. It is logically impossible to kill more than 100% of susceptible pine, so less than 50% must have been killed in at least some "severely" infested areas.

As we have noted before, there are two issues confounding percent kill estimates in the provincial overview data. First, observers tend to overestimate the proportion of red in a stand, and second, last year's attack can sometimes be mistaken for current attack. So it is

not a surprise that the aerial overview survey tends to overestimate beetle kill, especially when infestations are "severe".

It is the most severe infestation class that cause the most problems, and that we suspect is most wrong. In the absence of more guiding information, we have decided leave the other infestation classes as they are. We reduce the threshold for a "severe" infestation from 30% to 20% kill, and the mid-value for this category to 30%. Using these numbers, areas can logically remain severe for up to 3 years. We assume after that point that the infestation subsides, and edit the infestation severity maps accordingly. The updated severity classifications are:

	Lower	"Mid"	Upper
Severe	0.2	0.3	1
Moderate	0.1	0.15	0.199999
Low	0.01	0.05	0.099999
Endemic	0.000001	0.005	0.009999
None	0	0	0

Table 2: Proportion of pine affected by beetles according to our reinterpretation of the aerial survey data, in light of the fact that more than 100% of pine cannot be killed over the extent of an infestation.

2 Projection Model Overview

2.1 Basic approach

Our beetle projection model is a discrete probability transition model that runs on an annual time step. Each location in each year will be in one of five beetle states, or infestation severity classes -- NoMPB, Endemic, Low, Moderate, or Severe. The probability that a location will be in a given state depends on the conditions at that location in the previous year. The core of the model is a transition probability table with the following general form:

Conditions at time t			**Probability of beetle state, s, at time t + 1**				
Index (m)	Factor 1	.. Factor n	NoMPB	Endemic	Low	Moderate	Severe
1	$class_{1,1}$	.. $class_{n,1}$	$P_{1,NoMPB}$	$P_{1,End}$	$P_{1,Low}$	$P_{1,Mod}$	$P_{1,Sev}$
...	...	.. $class_{n,1}$	...	...	...	...	...
...	$class_{1,i}$	.. $class_{n,1}$	...	...	...	...	...
...	$class_{1,1}$	.. $class_{n,2}$	...	...	...	...	...
...	...	.. $class_{n,2}$	...	...	...	...	...
...	$class_{1,i}$	.. $class_{n,2}$	...	...	...	...	...
...	...	.. ...	...	...	...	...	...
...	...	.. ...	...	...	...	...	...
M	$class_{1,i}$	.. $class_{n,i}$	$P_{m,NoMPB}$	$P_{m,End}$	$P_{m,Low}$	$P_{m,Mod}$	$P_{m,Sev}$

Table 3: General form of the transition probability table that underlies the mountain pine beetle projection model.

Factors affecting the probability of a given beetle state at time t include the beetle state in the previous year, the cumulative amount killed by beetles at that location in all previous years, the age, percentage of pine, and climatic conditions of the stand, and the amount of beetle pressure from nearby infestations. We parameterize the transition table by classifying the conditions at each location in each year of our data (1999 – 2002). Each location will be assigned a class value for each of n factors. The combination of class values constitutes a location type or condition, each of which is assigned a unique index value, m. We then count the number of cases in each condition and the number of times that that a given beetle state follows each condition. The probability of future beetle state s given cell condition m is:

$$P_{m,s} = \frac{\text{Number of Locations}_{m,s}}{\text{Number of Locations}_{m}} \qquad \text{Eq. 2}$$

We have found it conceptually useful to group cell conditions into one four main categories. First, we distinguish between infestations that are already in progress, and those locations where there are not yet any beetles. Locations without beetles are further divided into areas within 1 kilometre of a current infestation, areas near enough to a current infestation to be subject to significant long-distance beetle pressure, and areas so far from current infestations that any beetle activity is likely to due to increases in local

beetle populations, rather than immigration of beetles from other areas. We refer to these latter three categories as "local", "long-distance", and "emergent" respectively (Figure 2).

It is worth pausing for a moment here to examine the concept of "beetle pressure" in more detail. It remains a matter of some uncertainty and controversy to how often beetles disperse farther than 1 km, and how much dispersal contributes to infestations in more distant locations. We do not have enough information to settle the question at this time.

What we can say without doubt is that infestations are more likely arise nearer to current infestations than further away from them. This might be either due to beetle dispersal from one location to another, or because locations near to one another tend to be subject to similar weather and climatic conditions that affect the growth of beetle populations. In our conceptual model, we have favoured the dispersal hypothesis over a more environmental approach, largely because we don't have much information about environmental factors.

It is not our intent to gloss over the uncertainty in this area, nor to claim we understand beetle dispersal and the role it plays in infestation spread. Rather, our aim is to do the best job of predicting the pattern we see given the information we have available. We have done our best to include important factors, and being able to recreate the past gives us some comfort that the model is reasonable. But we may have missed some environmental factors that will be crucial for driving future infestation dynamics. We would welcome any input about what these factors might be, especially if accompanied by data we could use to drive an alternative model. In the meantime, our model predicts what might to happen if beetle dispersal pressure, stand age, percentage of pine and current infestation status are the main drivers of outbreak dynamics. We do not claim that these factors are sufficient, only that they are the best we have come up with so far.

2.2 Infestation start model overview

Formally, locations are potential "start" locations if:

- habitat is suitable (percent pine > 0 and bec zone is suitable)
- stand age is greater than 60 years
- there is no current infestation
- cumulative kill by beetles in this location is less than 100%

Given that the preceding necessary conditions are met, the probability of an infestation of given severity arising depends on:

- stand age
- local beetle pressure
- long-distance beetle pressure
- percentage of pine in the stand

See Section 4 for explanation of how beetle pressure is calculated. See Section 5 for discussion of the relationship between cell conditions and infestation start probabilities.

2.3 Infestation progression model overview

An location is "in progress" if:

- habitat is suitable (percent pine > 0 and bec zone is suitable)
- age is greater than 60 years
- there is some current infestation

The progress of infestations that have already started depends on:

- current infestation severity
- cumulative percentage of pine killed by beetles in all preceding years
- percentage of pine in the stand
- local beetle pressure

See Section 6 for more discussion of this aspect of the projection model, and some exploration of the relationship between cell conditions and the progress of infestations.

3 Calculation of beetle pressure

I define "beetle pressure" as a measure of the dispersal pressure sustained in each cell. It is basically an estimate of the number of beetles that will arrive in a cell from other locations, but readers should keep in mind two distinctions between that quantity and the more conceptual "beetle pressure" measure. First, while the number of beetles that arrive in any location will be stochastic, beetle pressure is an entirely deterministic measure of the expected attack level in each cell. Second, while we hope that the relative ranking of beetle pressure values will be meaningful, we have no great faith that our estimated beetle numbers will be accurate.

The "beetle pressure" calculation can be broken into several components:

- Get the number of "source" beetles. This is the expected number of beetles that will be produced at each location given the history of beetles at that location and stand characteristics (age and percent pine).
- Tabulate wind speed and direction information by forest district.
- Devise some method of distributing long-distance dispersers given wind information.
- Devise some method of distributing short-distance dispersers given the relative "attractiveness" of neighbouring cells.

3.1 Get number of "source" beetles

To estimate the number of beetles dispersing from each location, I rely on results from a stand level mountain pine beetle model developed by researchers at the Canadian Forest Service (ref). Predictions from this model across a range of forest stand conditions and beetle attack levels have been tabulated for use in the regional scale MPB/SELES model. This table indicates number of beetles that will be produced and level of damage expected given a range of forest and infestation conditions. In particular, the table contains the following information:

Category	Heading	Description
Predictors – forest attributes	age	age of stand
	si	site index of stand
	sph	density of stand
	pcp	percentage of pine within stand
Predictors – infestation attributes	year	number of years since the infestation began
	numAttackers (t-1)	number of beetles that attacked this stand last year (t-1)
Resultant –	numDispersers(t)	number of emerging beetles that disperse out of the source stand this year (t)
	numLocal(t)	number of emerging beetles that remain in the source stand this year (t)
	percentVolKill	green attack last year (t-1) or red attack this year (t)

Table 4: Structure of the table summarizing output from the stand-level mountain pine beetle model developed by the Canadian Forest Service.

Unfortunately, we cannot use the information in CFS table directly, because do not know the site index or stem density of our stands, nor to we know the exact number of attacking beetles in the stand last year. Basically, we need to predict the number of beetles that will disperse from a location a given the proportion of pine killed in that year, and the age and percentage of pine in the stand.

First, I classify each *percentVolKill* number in the table into one of the five attack severity classes (Table 2). I also calculate the cumulative percentage of volume killed over all previous years of the infestation by summing *percentVolKill* over years 1 to t of the infestation, where t is the current value of *year*. I round this cumulative volume kill to the nearest 20% to get one of 6 *cumVolKill* classes.

I calculate the average number of dispersers and local beetles in each category to get a table with the following columns:

Category	Heading	Description
Predictors – forest attributes	age	age of stand, classified
	pcp	percentage of pine within stand, classified
Predictors – infestation attributes	currSeverity	Percent of pine red-attacked this year (i.e. killed last year), classified
	cumVolKill	Percent of pine killed over all previous years, classified.
Resultant –	numDispersers	number of emerging beetles that disperse out of the source stand this year (t)

Table 5: Structure of the table in BCMPB to provide the number of dispersers emerging from each infested cell.

3.2 Tabulate wind speed and direction

We obtained daily wind speed and wind direction data from weather stations around BC from July 24-Aug15 1970-1995. The "daily" readings are taken for 10 minutes around noon of each day. On the assumption that most of the flight happens in the second week of August, we used data from August 5 to August 15.

I calculated the proportion of times the wind blew in a particular direction and the average speed of wind in each direction over the entire data period (Aug 5 to Aug 15, 1970-1995). Since the location data we have for weather stations is accurate only to within the nearest degree, we group data from weather stations within each forest district.

Wind speed is given in metres per second, and wind direction is rounded to the nearest 45°. Angles are assigned according to geographic convention, where 0 degrees is due north, and angles increase in a clockwise direction through east to south to west and back to north. According to meteorological convention, the "direction" of a wind is the direction from which that wind came. Thus, a north wind will blow beetles to the south from their source location. For reference, direction categories are assigned and referred to as follows:

Direction ID	Description	Angles
N	Wind blows from north to south.	337.5-22.5°, from destination to source cell.
NE	Wind blows from northeast to southwest.	22.5-67.5°, from destination to source cell.
E	Wind blows from east to west.	67.5-112.5°, from destination to source cell.
SE	Wind blows from southeast to northwest.	112.5-157.7°, from destination to source cell.
S	Wind blows from south to north.	157.7-202.5°, from destination to source cell.
SW	Wind blows from southwest to northeast.	202.5-247.5°, from destination to source cell.
W	Wind blows from west to east.	247.5-292.5°, from destination to source cell.
NW	Wind blows from northwest to southeast.	292.5-337.5°, from destination to source cell.

Table 6: Summary of wind direction categories.

I omit from the tabulation days with no wind at all. This is equivalent to saying that beetles will wait until there is wind before rising above the canopy for long distance dispersal. For reference, Appendix 1a contains the broad summary of the frequency of prevailing wind directions across the province that we use. Appendix 1b contains the average wind speed in each direction.

3.3 Long-Distance Dispersal

I get the total number of dispersers given age, percent pine, and infestation severity in each location in each year from the information calculated in Section 3.2. These are the "source" dispersers in each location, *numSource*. I assume that some constant proportion of these dispersers will travel long distance. The actual proportion is not important, because long and short distance beetle pressure will be independent factors in the model, and beetle pressure is a dimensionless quantity.

Wind speed and frequency vary with direction. The probability that dispersers will travel on winds coming from a particular direction is given in Appendix 1a.

I assume that long distance dispersers travel at wind speed until they land. Thus, beetle flight times will be exponentially distributed with a mean of *aveFlightTime*, where:

$$landRate = 1/aveFlightTime \qquad \text{Eq. 3}$$

and the probability of any particular flight time, t, is:

$$P(t) = landRate * e^{-t * landRate} \qquad \text{Eq. 4}$$

In MPB/SELES a constant landing rate of 0.01 per hundred metres is used for long-distance dispersers. Assuming a typical wind speed of 10 metres per second, this translates to a landing rate of 0.001 per second, and an average flight time of approximately 20 minutes, or 0.3 hours.

Once selected, wind speed and direction are assumed to be constant throughout the beetle flight. Thus, the distance traveled by each beetle (x) is equal to the flight period of that beetle multiplied by the wind speed, *currWS*:

$$x = t * currWS \qquad \text{Eq. 5}$$

The average flight distance of beetles is:

$$E(x) = aveFlightTime * currWS \qquad \text{Eq. 6}$$

Given an average wind speed of 10 m/s and an average flight time of 20 minutes, beetles will travel 12 kilometres on average.

Conceptually, the simplest thing to do would be to disperse beetles from each source over a region up to the maximum distance beetles can travel in each direction. However, at a wind speed of 10 m/s, a beetle can travel 108 kilometres in three hours. A circular region with a diameter of 100 km encompasses approximately 200,000 cells in our model. In 2003, there are 195,301 infested cells in British Columbia, each producing some dispersing beetles. On the computers we have available, it takes between 30 seconds and 1 minute to calculate the beetle plume from one source. Multiplying by 195,301 sources, we get a calculation time of between 68 and 136 days for one beetle pressure map for one year.

Clearly, it is not practical to disperse beetles from each source cell independently. Instead, we employ a moving-line type algorithm, where beetles are "smeared" across the landscape in each of 8 wind directions, in much the same way that paint might smear across a canvass on which paint is spattered, and then smeared with a window squeegee. Here the analogy breaks down a bit, because it is impossible to draw the squeegee across the canvas simultaneously in each wind direction, but this is effectively what we do.

More formally, the beetles dispersing from each source are divided into eight groups, each of which will travel in a given wind direction. The proportion of beetles traveling in each direction depends on which forest district the beetles come from (Appendix 1a). We specify a "moving-line" vector, big enough to span the beetle map (slightly longer than the longest diagonal). Beginning with the "North" wind, we start at the top of the beetle map with a line that contains no beetles. Moving from top to bottom (North to South), we pick up dispersing beetles from each source as we pass over. The line carries these beetles southward. At each step, some proportion of beetles being carried by the line are placed back on the landscape. The proportion of beetles deposited depends on the landing rate of beetles (Equation 3) and the average wind speed at that location in that direction (Appendix 1b). While beetles are carried forward by the line, they also diffuse laterally; at each step, 40% of beetles are moved to the adjacent cell in each direction (20% in each direction), and 40% are moved 2 cells away in each direction. 20% of beetles remain in place. When we arrive at the bottom edge of the map, we repeat the spreading process for each of the 7 other wind directions.

Figure 3 shows the results of this smearing process for 2002. First, we see the price that is paid for the greater computational efficiency of our moving line algorithm in the star patterns that form around our beetle sources. This computational artefact could be countered by increasing the number of "swipes" we take with our moving-line, but this takes time. The map shown seems to us an acceptable compromise.

Figure 3 shows at least some amount beetle pressure everywhere in the province. The lowest value represents an expectation that approximately 1/10,000,000,000 of one beetle will at this location per year. Clearly, such a small likelihood of dispersal probably has no

real effect on beetle dynamics in these areas. In the current version of the model, we have chosen to consider long-distance beetle pressures of less than 2.25 as negligible. This is a somewhat arbitrary decision, and we would appreciate any input or insight on the subject. Beetle pressure values above 4.75 are considered uniformly "high", and we resolve beetle pressure classes to a width of 0.5 units per class. Figure 4 shows the classified beetle pressure map for 2002. Depending on the severity of source infestations, and local wind speed, long-distance beetle pressure can be significant up to 60 or 70 kilometres away from the source.

3.4 Short-distance dispersal

Dispersers that do not travel long-distance distribute themselves among cells within one kilometre of their host cell. In general, the probability of beetles dispersing to a location depends on the quality of habitat at that location, the distance from the source location, the direction of the prevailing wind, and the number of beetles already at that location. As much as possible, I have tried to follow the approach to short-distance dispersal used in SELES/MPB. However, that model takes an iterative approach to short-distance dispersal, where later dispersing beetles make decisions based on the movement of earlier dispersing pioneer beetles. Here, we aspire to a more efficient one-step dispersal model, and so must take a somewhat different approach.

First, in SELES/MPB, the probability that a beetle will move to a particular location is:

$$0.00000001 + distanceFactor * hostFactor * windFactor * hostFactor * pheromoneFactor \quad \text{Eq.7}$$

Where:

$$distanceFactor = 1/d^2 \quad \text{Eq. 8}$$

d is the distance from the beetle source in cell widths. I adopt this portion of the model as it is.

The *hostFactor* in SELES/MPB is:

$$hostFactor=(1-cumKill/100)*SusceptibilityIndex/100 \quad \text{Eq. 9}$$

I cannot adopt this approach directly because we are missing some of the information necessary to calculate the susceptibility index. Using the information we do have, I calculate the *hostFactor* as:

$$hostFactor= (1-cumKill/100)* (age>60)*pcp/100 \quad \text{Eq. 10}$$

Again using the information available, I take the *windFactor* directly from Appendix 1a. *windFactor* varies with forest district and the direction to the source location. See Section 3.3 for more details.

The effect of the *pheromoneFactor* is to attract beetles to areas with some other beetles, and repel them from areas that are too crowded. The problem is that I wish to move all beetles simultaneously. Thus, I move beetles on the basis of wind, distance, and host quality alone, and omit the pheromone factor from this model.

4 Infestation start model

4.1 Stand age

Figure 5 shows the effect of stand age on the probability that infestations will start. Overall, infestations are most likely to start in intermediate aged stands (141-160). Although the overall probability of infestations starting declines with age thereafter, the probability that new infestations will be severe continues to increase.

4.2 Beetle pressure

Figure 6 shows the effects of both local and long-distance beetle pressure on infestation start probabilities. As should be, start probability increases with both local and long-distance beetle pressure. The distinctions between local and long-distance beetle pressure, and the method we use to calculate these factors, are explained in detail in Section 3.

4.3 Percentage of pine

Figure 7 shows the effect of percent pine on infestation start probabilities. Overall, infestations are most likely to start in stands that are 75-99 % pine. There is more chance that that an infestation will become severe immediately in stands with less pine. This makes sense when we recall that infestation severity is a measure of the proportion of pine that is killed in a stand. Basically, in a stand with only 30 pine trees, is beetles kill 15 trees the infestation will be severe. If beetles kill 15 trees in a stand with 3000 pine trees, the infestation will be endemic. It is more perplexing to note that start probability is less in stands that are 100 % pine. A closer look shows that 100% pine stands tend to be younger and subject to less beetle pressure than stands classified as 75-99% pine (Figures 8 to 10). Stands subject to more beetle pressure are more likely to be infested.

<<Note – I need to do some statistics to test whether the difference between the 75-99% and 100% pine classes is significant given these other factors. My statistics program seems to demand a full binomial array, rather than a summary with sample size and the proportion of successes in each group. I wonder whether SAS might accommodate the data in the form I have it, and whether it might be more efficient to just get Don Sachs to run a test for me, rather than for me get into strange and time-consuming data contortions necessary to make it work here.>>

5 Infestation Progression Model

5.1 Overview

Projecting infestations forward using information from the provincial overview data is problematic because infestation progression in some areas is confounded by changes in survey protocol over time, because we have no management history, and because the time-series only extends for 4 years. For these reasons, I am relying on output from SELES/MPB to guide the projection model. In future, it may be interesting to compare and supplement this information with some analysis of the provincial overview data, but for now I use only the SELES/MPB information.

5.2 Severity last year

Figure 11 shows the effect of infestation severity in the preceding year on infestation severity in the future. As might be expected, severe infestations are more likely to persist than milder ones. However, if we project future severity based this factor alone, infestations could persist to kill much more than 100% of the available host resource. Presumably, there must be some limit on persistence set by the cumulative amount killed.

5.3 Cumulative percent kill

First, in SELES/MPB we know the precise amount of pine that has been killed by beetles. In contrast, we will not know exactly how much pine has been killed, but must rely on estimates of the average percent killed in each severity class. Since the range of actual values in a class (especially the severe class, which ranges from 20-100%) is very large, cumulative percent kill estimates derived by this method tend to be fairly imprecise. It is worth taking a moment to first examine the actual effect of cumulative kill on the progress of infestations, and then investigate the effect of uncertainty in our cumulative kill estimates.

Looking first at the actual kill data, we see that infestations are most likely to persist when cumulative kill is between 10 and 50% (Figure 12). When cumulative kill is very low, the infestation has likely not yet had a chance to escalate. As cumulative kill increases, beetles eventually begin to run out of food. If beetles persist to kill more than 80% of pine, they are likely to continue to kill more than 90%. No beetles persist once 100% of pine has been killed.

Using mid-values in Table 2 to calculate the approximate percent kill, I get the results shown in Figure 13. Here, although the general trends remain apparent, the certainty that infestations that run out of food will subside is obscured by imperfect knowledge of the actual percent kill. To force a solution to this problem, I will terminate infestations artificially when the estimated percent kill reaches 100%. Figure 14 shows the final classification scheme.

5.4 Habitat quality

The persistence of infestations depends on habitat quality. As might be expected, infestations are more likely to persist in less mixed, more purely pine stands (Figure 15). Age, on the other hands, has relatively little effect on the persistence of infestations (Figure 16). The probability that infestations will become or remain severe or moderate is highest in stands of intermediate age (100-140 years old), but this effect is slight compared to the effect of other factors (Figures 10-14).

In general, we run a risk of over-specifying the infestation progression portion of the model, including so many levels of so many factors that there are not enough cases of each type upon which to draw convincing conclusions. Given that the effect of age is so slight, I have chosen to omit if from the infestation progress model at this time. In future, we could generate more SELES/MPB output with which to parameterize this model, which would allow us more freedom to include an age factor without over-specifying the model.

5.5 Local pressure

Finally, whether or not infestations subside, persist, or escalate also depends on external beetle pressure (Figure 17). Infestations tend to get more severe when there are many dispersers arriving from nearby cells. Note this part of the model is thus far premised on the assumption that local beetle pressure as calculated in Section 3 is a good estimate of the actual number of beetle arriving at a location. It might be worth spending some time addressing this assumption in future work.

6 Projection model testing

We parameterized the projection model using data from 1999 to 2002. Our main test of the model was to see how well we could project 2003 using this model. Out of curiousity, we also projected each year from the preceding year (2000 from 1999, etc). We also ran from 1999 through to 2003 to see how errors in the model might compound over years.

We will examine in some detail the nature and spatial distribution of errors in the 2002-2003 projection. Before moving on to these more detailed analyses. Figure 18 compares the cumulative pine volume killed by beetles in the observed data to our various projections. When we project just one year forward (1999 to 2000, 2000 to 2001 and so on), we over-predict in the first two years, and under-predict after that. This means that there are differences between years that are not being captured in our model. The rate of increase from 2002 to 2003 is greater than we expect from knowledge of 2001-2002, and so on back through the years. If this trend continues into the future our model will tend to under predict the progress of the infestation. We will return to this issue later. First, though, we turn our attention to understanding the dynamics of the model in more detail. Note that all numbers reported here are for the timber harvesting land-base only.

To give some context for the more detailed analysis, it is worth taking a look at the observed data from 2002 and 2003 (Figures 19 and 20) It is also worth noting that, according to Joan Westfall and Tim Ebata, the aerial survey data overestimates kill in the Chilcotin area in 2003.

A few discrepancies between the observed data and our prediction are immediately apparent (compare Figures 20 and 21). First, we fail to predict the new outbreak in the Chilcotin, to the south of the current outbreak. Second, our model predicts more endemic infestations will arise across the landscape than the data shows. Finally, we predict that severe infestations will subside to moderate intensity more often than the data shows.

In the model, we have made some distinction between infestations that are already in progress, infestations that start where there is significant local beetle pressure, infestations that start where there is only long-distance beetle pressure, and infestations that start in areas where there is no significant beetle pressure. To understand which components of the model might be performing worse than others, it is worth taking a more detailed at how the model performs in each of these four situations. Figure 22 shows the number of infested cells observed and predicted in each of these categories.

In the infestation in progress sub-model, we predict fewer severe infestations and more low and endemic infestations than the data shows. This accords both our visual observations, and our understanding of what the true situation may be.

First, consider our tendency to predict infestations will subside more often than the data shows. Recall that our infestation projection model is based on output from SELES/MPB, and that we suspect the overview survey tends to overestimate the amount of kill in heavily infested areas. Taking these factors into account, it does not surprise us that our model predicts a different trajectory for infestations in progress than the data shows. Furthermore, we do not trust the survey data enough for this discrepancy to cause us great concern.

Discrepancies between our model and the data in the start model, on the other hand, indicate that there is some difference between our projection year and the preceding years. This difference might be purely stochastic (i.e. particular wind conditions last year carried beetles much farther than we would expect in a particular direction), or they might be more systematic, indicative of some factors affecting beetles that we have not yet taken into account.

Figure 22 shows that in 2003 we significantly under predict emergent starts in all categories, and both local and long-distance low severity starts. I begin with the low infestation starts, which we under-predict mostly because we fail to predict the new Chilcotin outbreak. First, recall that the Chilcotin data probably an overestimates the actual kill be beetles in these areas. Second, I note that the pattern looks surprising. I do not know why beetles might have sprung up all across the Chilcotin in 2003, but I am not at all surprised that the model fails to predict this pattern, given behaviour of the outbreak over previous years.

That we under predict emergent starts so consistently is more concerning. Basically, there are two possibilities for why this might be. First, 2003 might have been a better year for beetles than other years. Alternatively, these starts are not really emergent, but depend on the prevailing beetle conditions. The latter possibility would suggest that the threshold at

which we consider beetle pressure to be negligible is too high. It may be worth revisiting this issue in future versions of the model.

Figure 23 compares observed and predicted values for the cumulative percent of susceptible pine volume killed by management unit. Figure 24 shows the spatial distribution of these errors. We tend to under-predict volume killed in more heavily infested management units – most conspicuously, Quesnel, Williams Lake, Lakes and Prince George. We over predict in a few moderately infested units including Morice, Robson Valley, and Merritt. We also do a poor job of predicting kill in a number of TFL's, but these areas are too small to merit serious attention.

7 Projecting forward

Our base run begins in 2004, runs for 20 years to 2023, and includes no management interventions. Figure 25 shows how the proportion of susceptible volume killed increases over that period. In 2003, beetles have killed 8.6% of susceptible pine in the province. It takes until 2010 for beetles to kill 55% of susceptible pine, and by 2023 96% of susceptible pine has been killed by beetles. The remainder of the figures (still missing) show how the spatial pattern of kill changes over time. The infestation in the central region of the province begins to subside by 2005, and has almost entirely subsided by 2009. By then, the Kootenays, Kamloops and more northern regions are fully infested. An outbreak in the far northeast of the province continues to escalate until approximately 2014, after which beetle populations slowly subside across the province. The outbreak in any particular region begins to subside after approximately 5 years, but it takes much longer for the beetles to eat up everything everywhere.

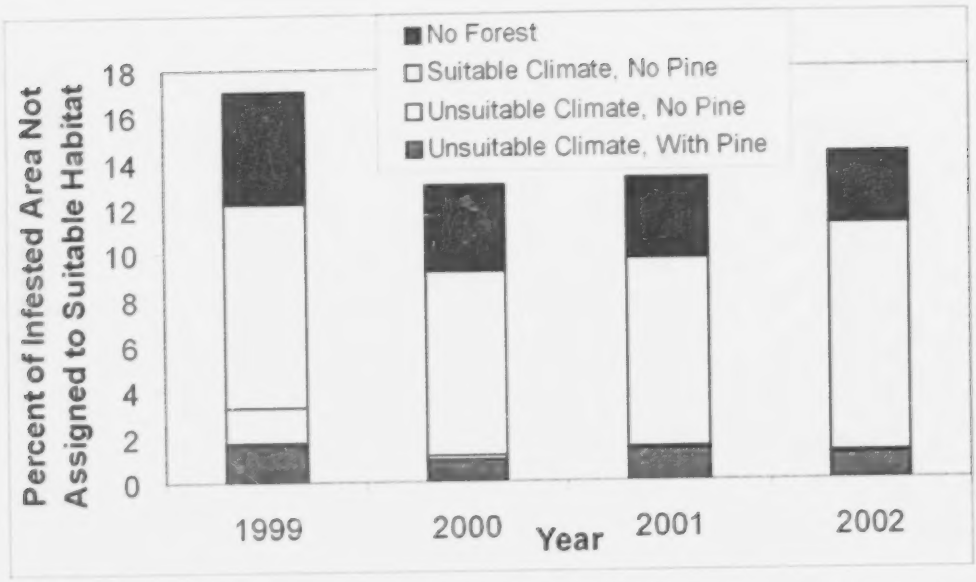


Figure 1: The aerial overview survey data reports more beetles in some areas than there is forest to accommodate those beetles. Where possible, we allocate beetles to adjacent suitable habitat, on the assumption that the spatial location of the infested polygon might not be exact. However, we do not find places to put all of the extra beetles. Here, we show the proportion of beetles lost, and the type of area in which they were lost.

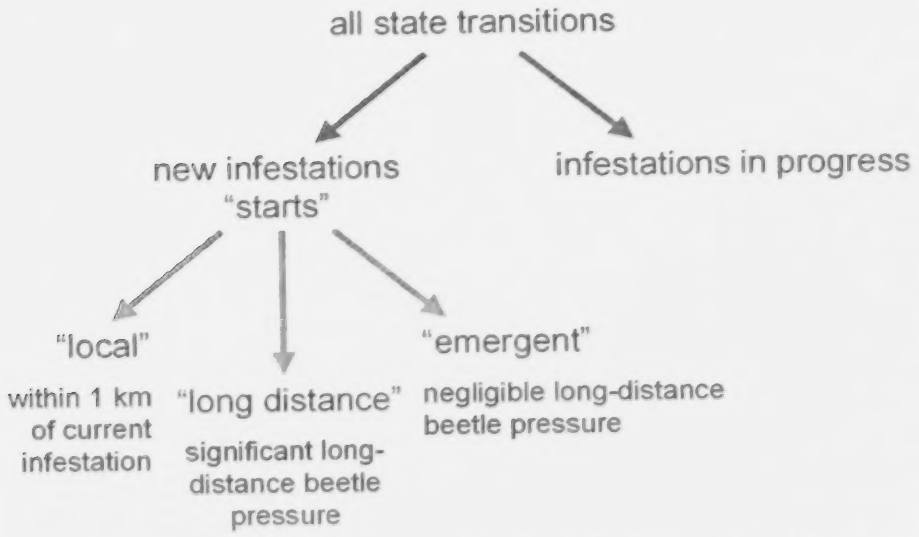


Figure 2: Four sets of conditions in the mountain pine beetle transition model. See Section 2.1 for further discussion.

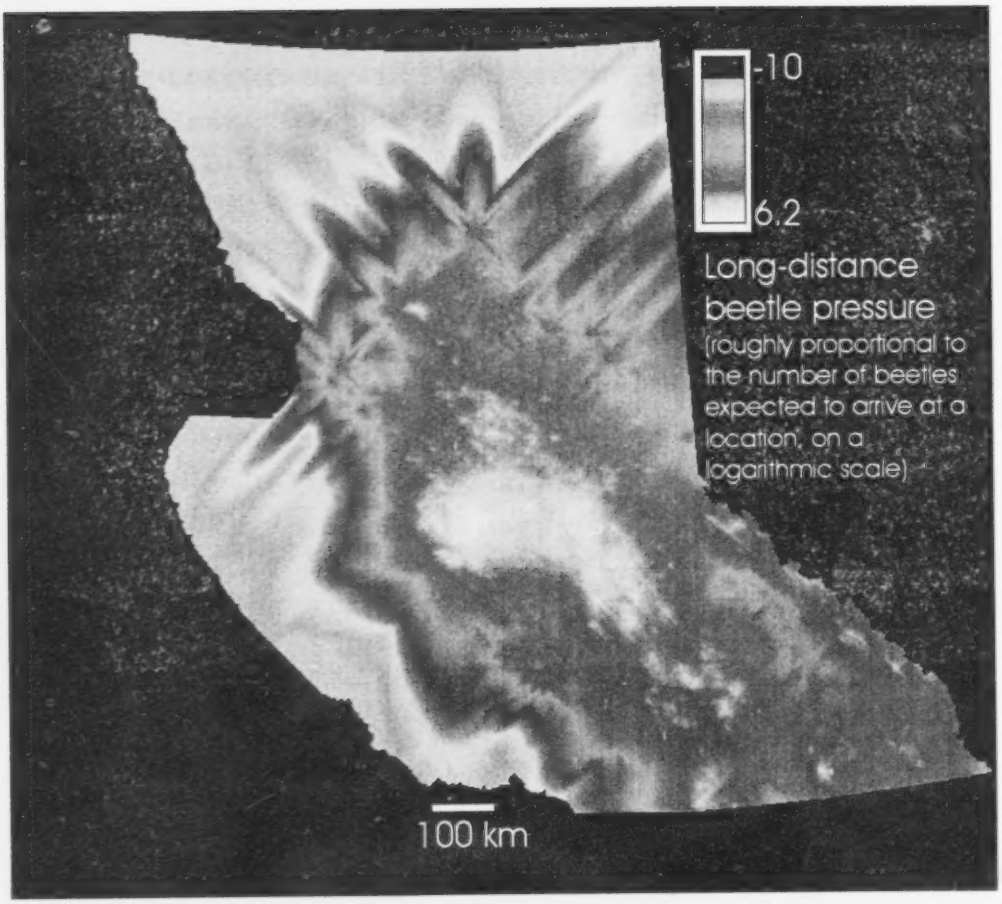
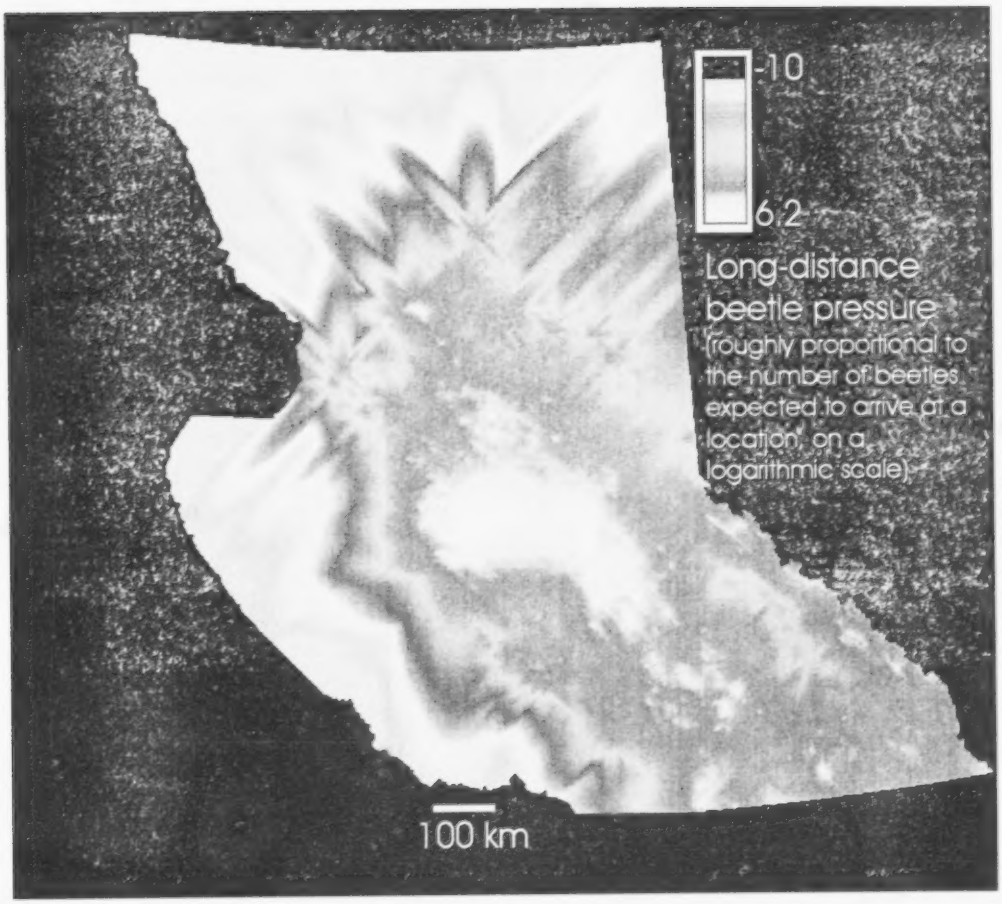

-10
6.2
Long-distance beetle pressure
(roughly proportional to the number of beetles expected to arrive at a location, on a logarithmic scale)
100 km

Figure 3: Long-distance beetle pressure in 2002, calculated using a moving-line algorithm. Beetle pressure is shown on a logarithmic scale. Pressure is a measure of the relative number of dispersing beetles expected to arrive at a location, but is a dimensionless quantity. To illustrate, we could reasonably expect that 10 times more beetles might arrive in an area with a beetle pressure of 2 than a beetle pressure of 1. We could not reasonably claim that 200 hundred beetles will arrive at locations with a beetle pressure value of 2.


10
6.2
Long-distance beetle pressure
(roughly proportional to the number of beetles expected to arrive at a location, on a logarithmic scale)
100 km

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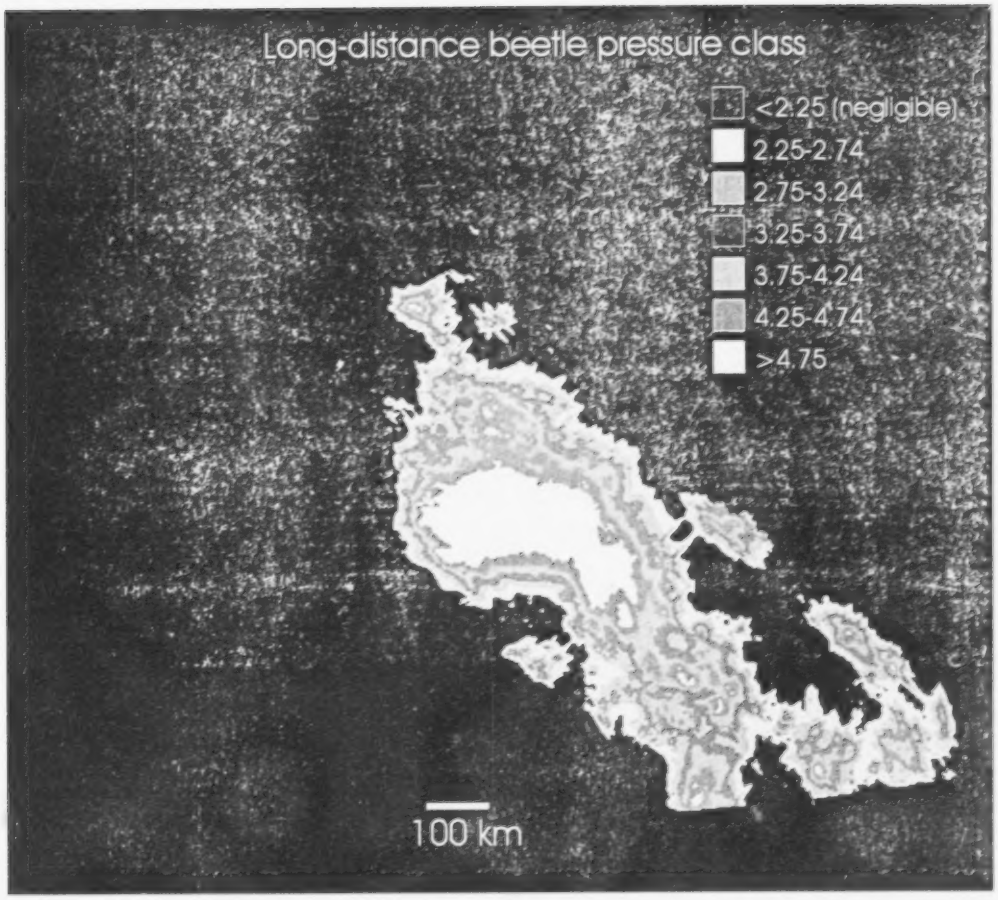
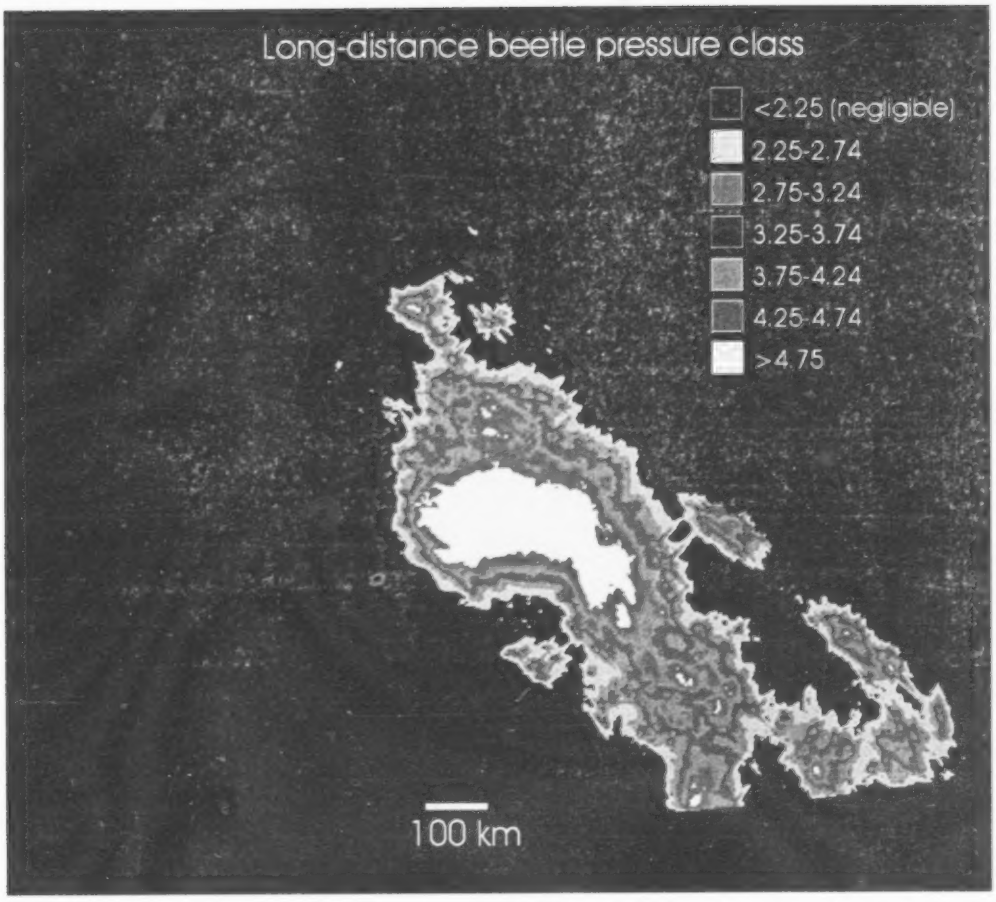


Figure 4: Long-distance beetle pressure classified into classes of 0.5 unit widths. Pressure values of less than 2.25 are considered negligible, having no significant effect on mountain pine beetle dynamics in these areas.



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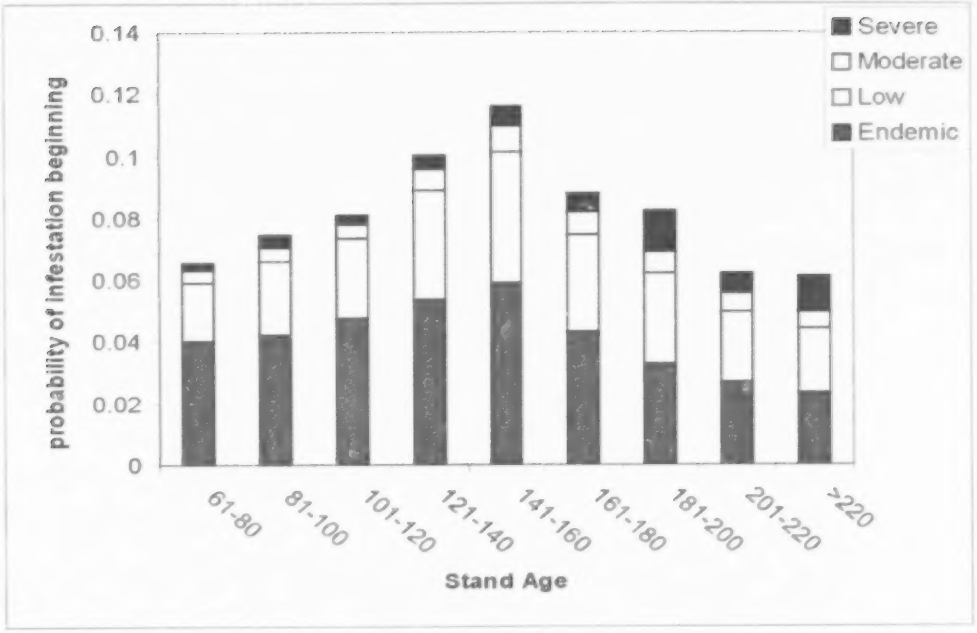

Figure 5: The effect of stand age on the probability an infestation of given severity will start in an area that is not currently infested.

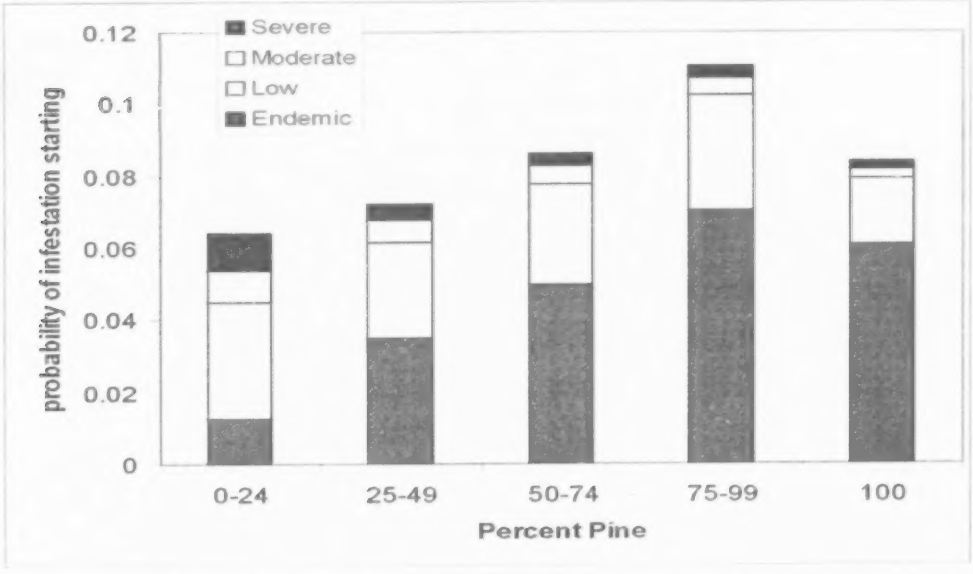

Figure 6: The effect of percent pine on the probability an infestation of given severity will start in an area that is not currently infested.

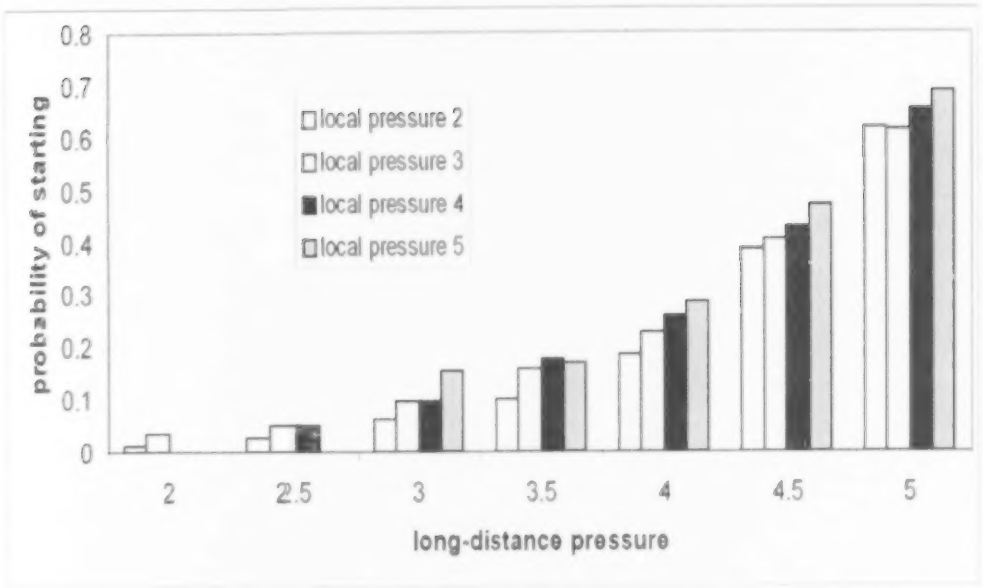

Figure 7: The effect of both long-distance and local beetle pressure on the probability an infestation of any severity will start in an area that is not currently infested.

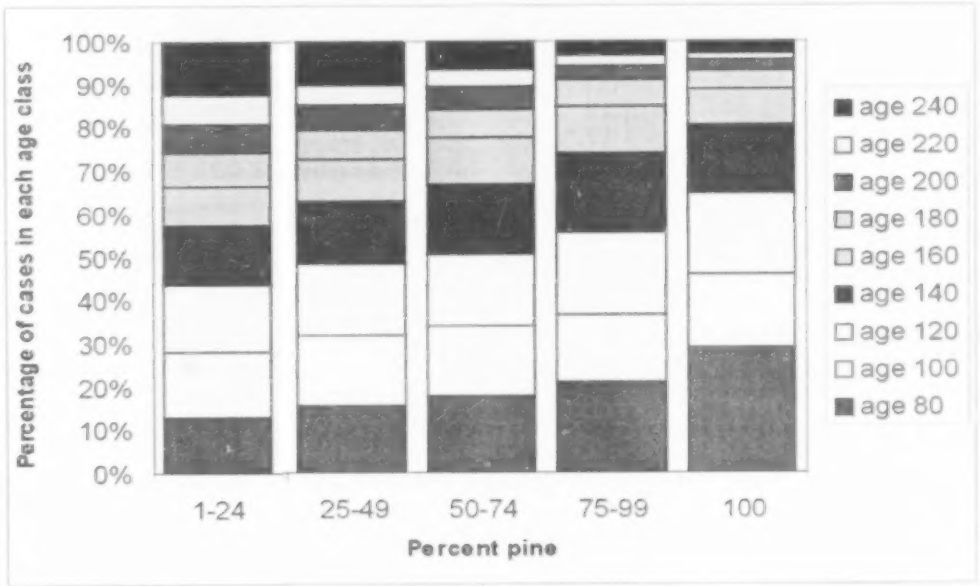

Figure 8: The relationship between age and percent pine. Stands with 100% pine tend to be younger than stands with 75-99% pine.

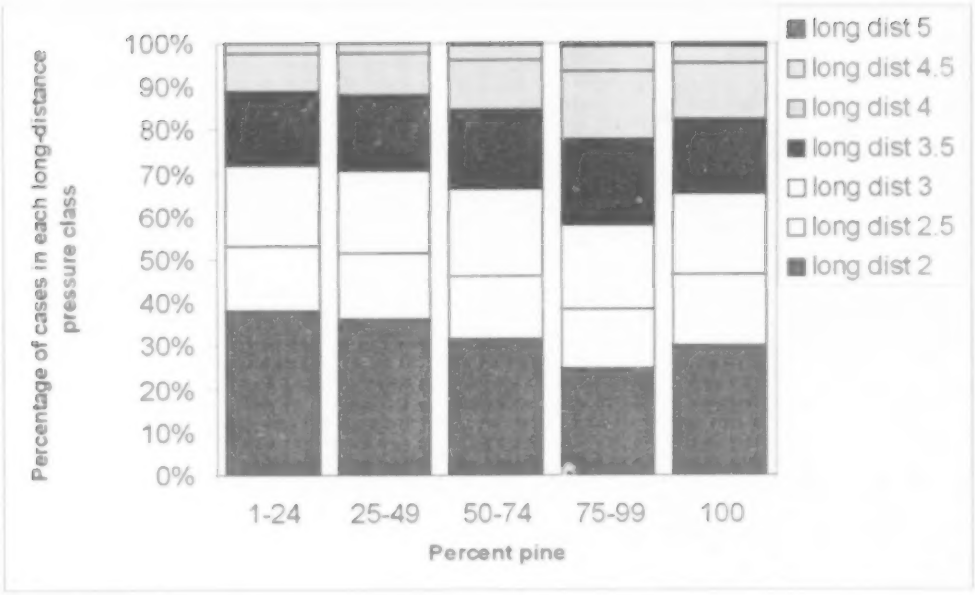

Figure 9: The relationship between long-distance dispersal pressure and percent pine. Stands with 100% pine tend to be subject to less long-distance beetle pressure than stands with 75-99% pine.

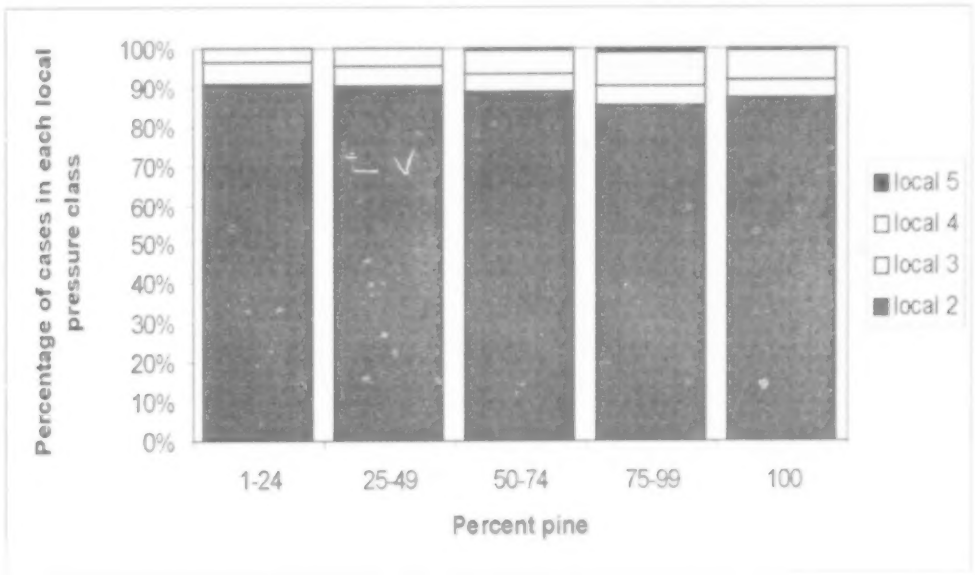

Figure 10: The relationship between local dispersal pressure and percent pine. Stands with 100% pine tend to be subject to less local beetle pressure than stands with 75-99% pine.

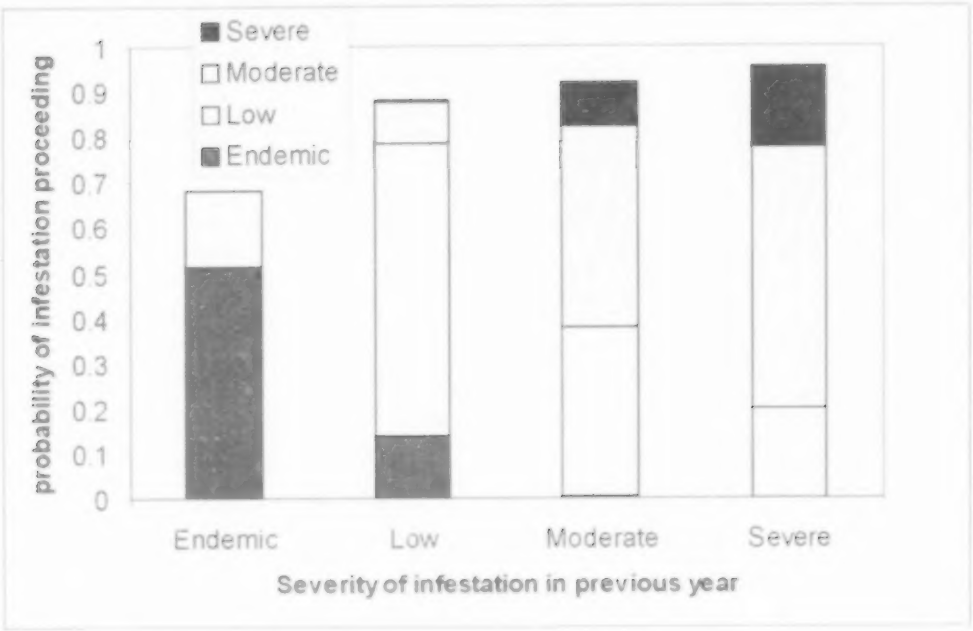

Figure 11: The effect of current infestation severity on future infestation severity.

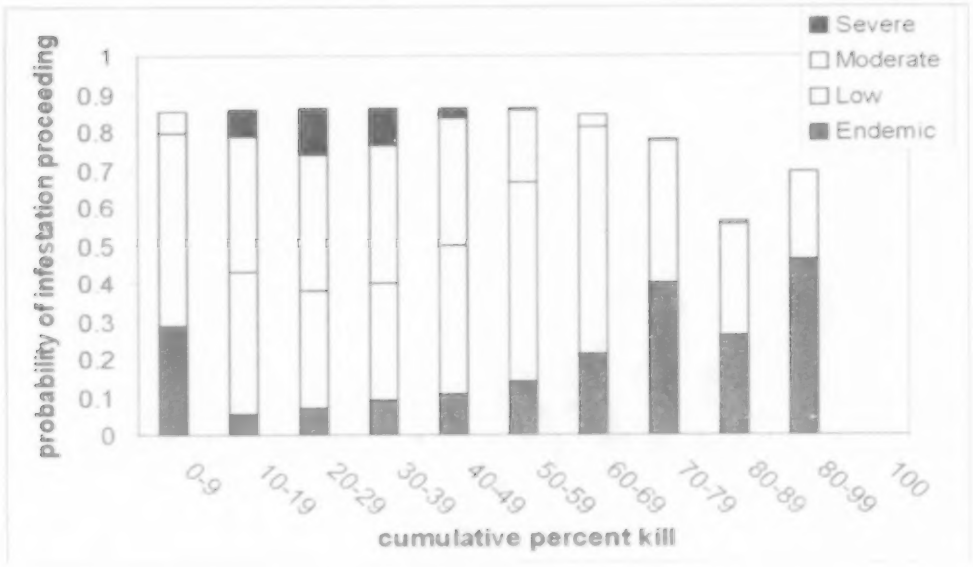

Figure 12: The effect of actual cumulative kill on future infesation severity. Cumulative kill values are exact, based on perfect knowledge of SELES/MPB, rather than estimated from mid-point values for each severity class.

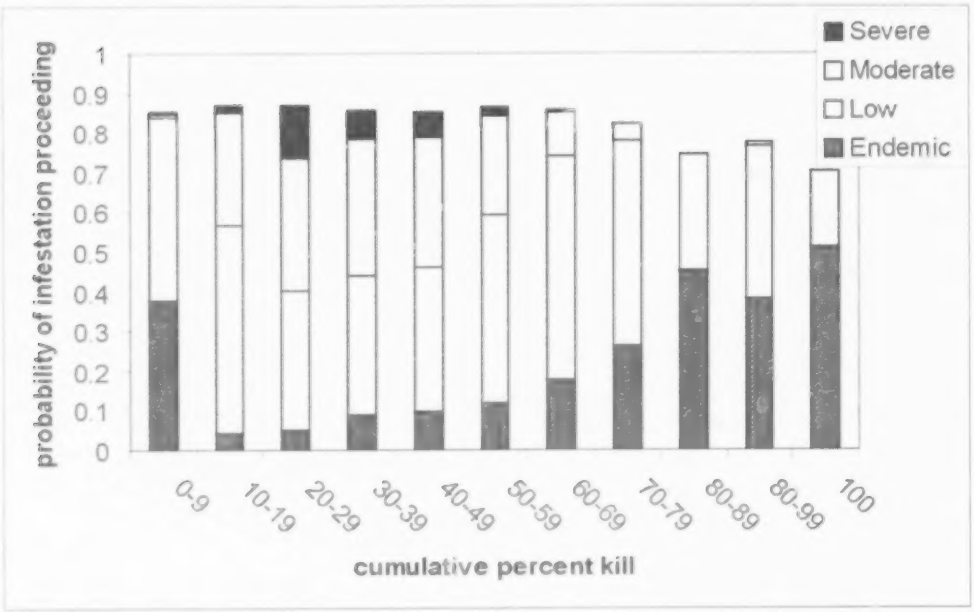

Figure 13: The effect of estimated cumulative kill on future infesation severity. Cumulative kill values are approximate, estimated from mid-point values for each severity class, rather than exact knowledge.

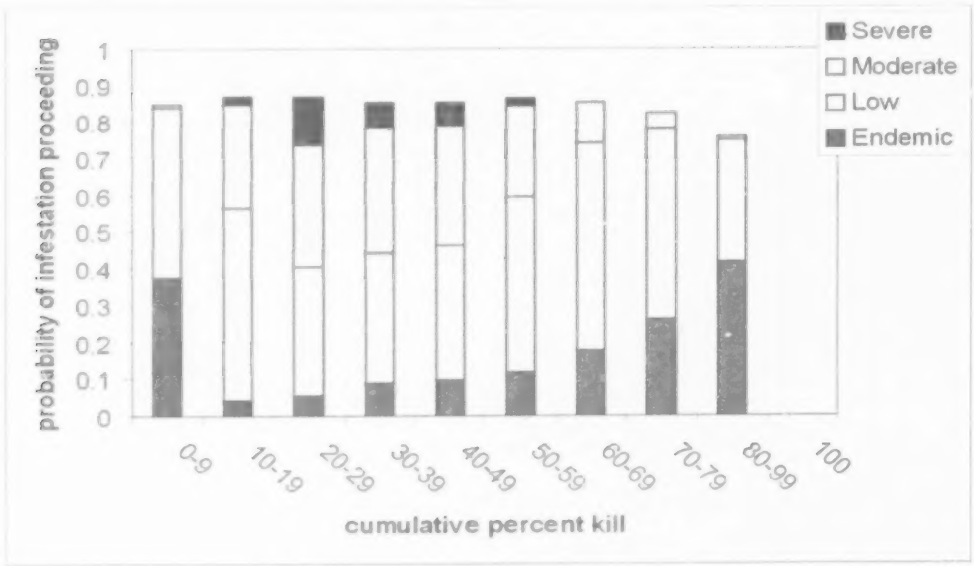

Figure 14: The effect of estimated cumulative kill on future infesation severity, modified to stop infestations from continuing after cumulative kill reaches 100%. Cumulative kill values are approximate, estimated from mid-point values for each severity class, rather than exact knowledge.

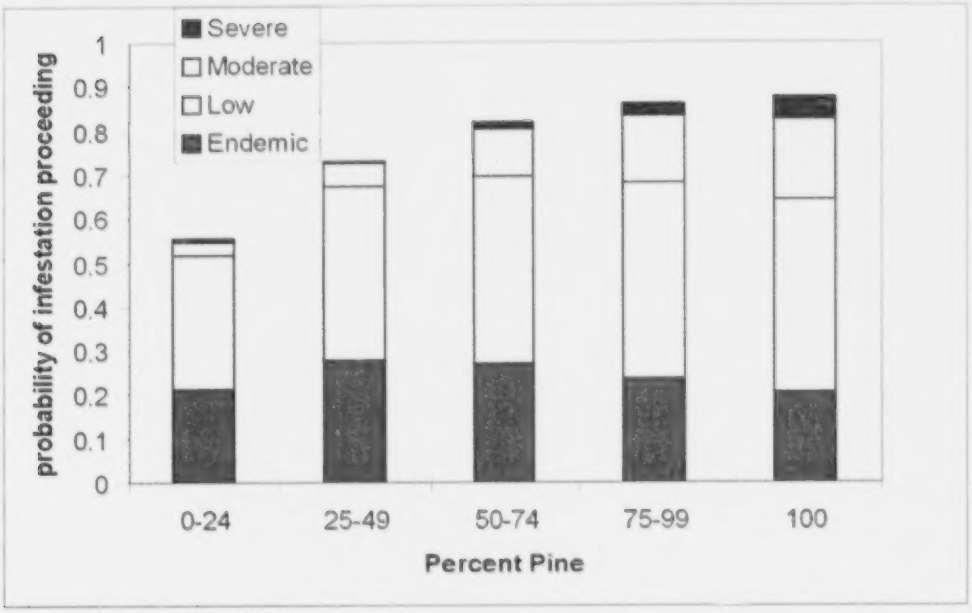

Figure 15: Effect of percent pine on the progress of infestations.

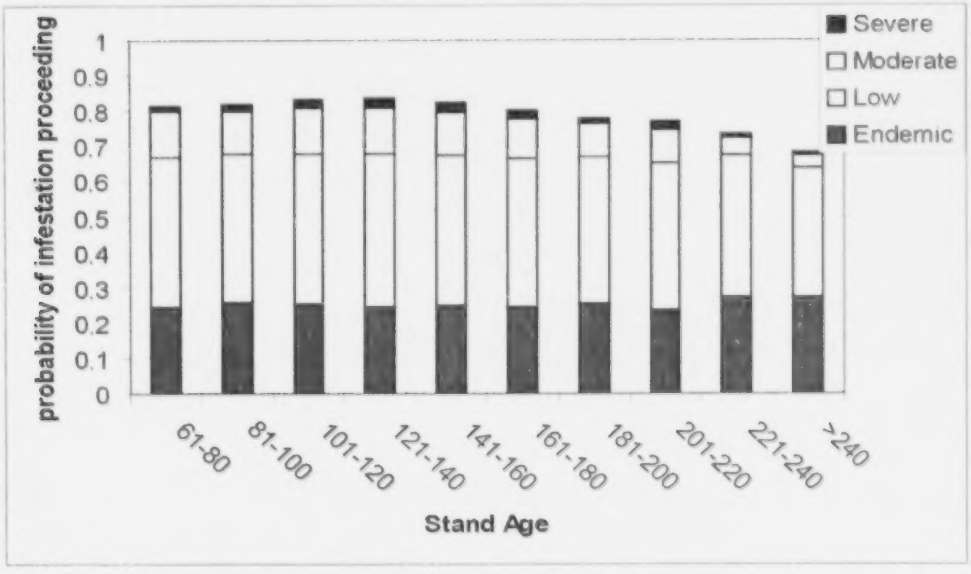

Figure 16: Effect of stand age on the progress of infestations.

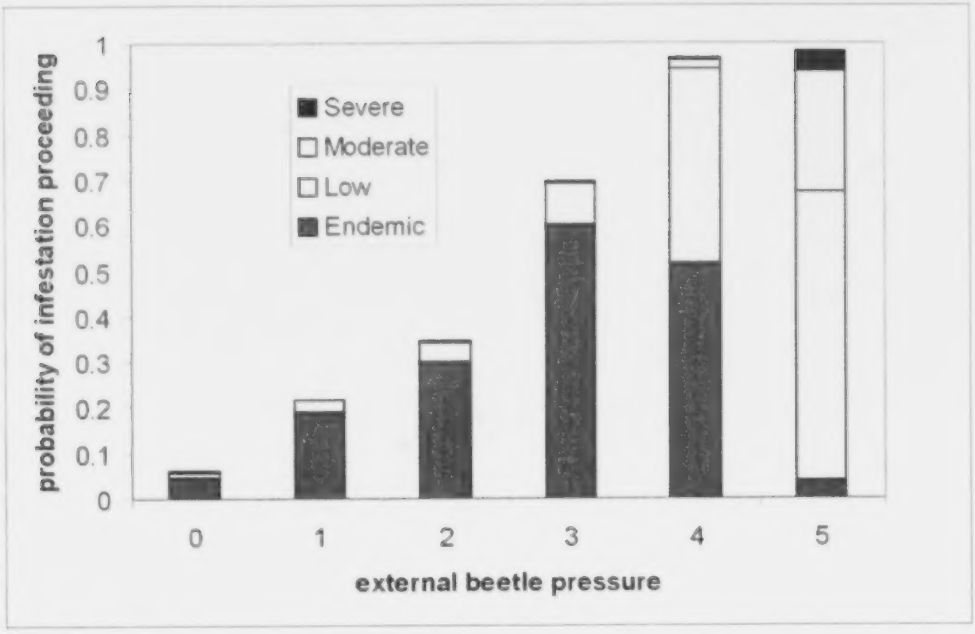

Figure 17: The effect of local beetle pressure on the progress of infestations.

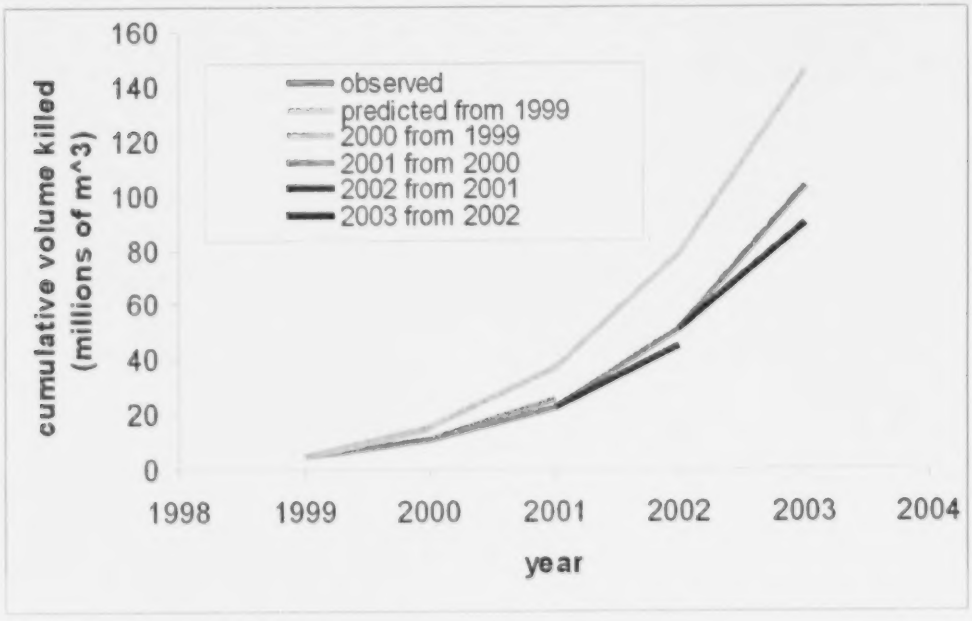

Figure 18: Cumulative pine volume killed by beetles across the timber harvesting land-base between 1999 and 2003. Predictions are from a projection model parameterized with 1999 to 2002 data, so 2003 is a "blind" test of the model.

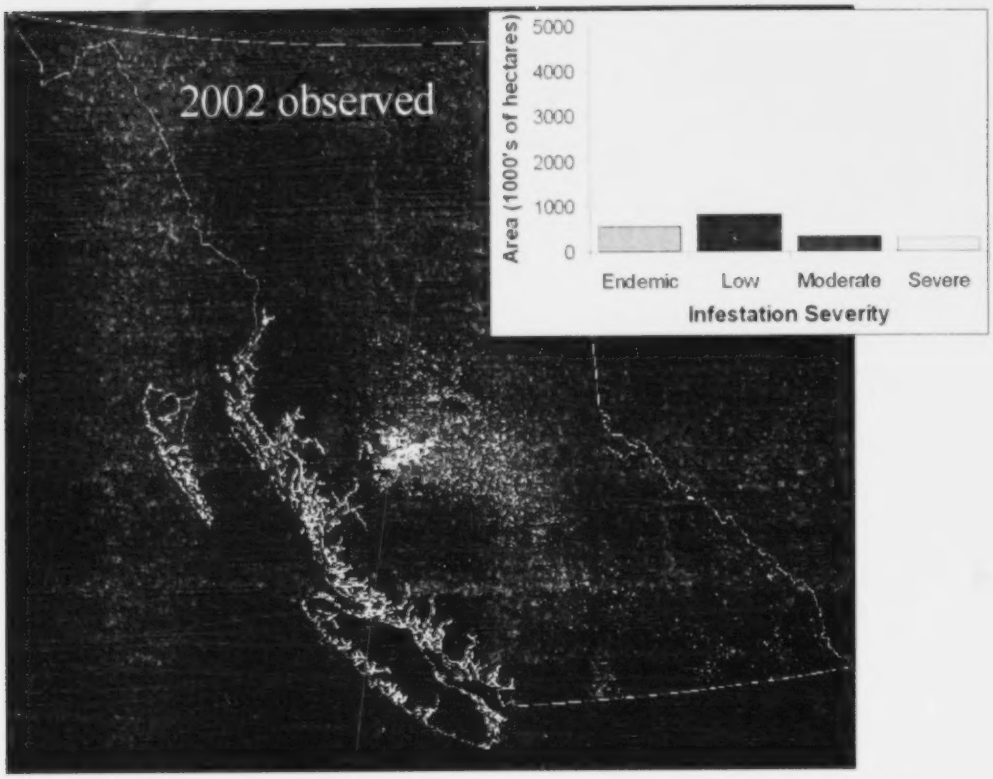

Figure 19: Mountain pine beetle infestation severity across British Columbia in 2002, according to aerial overview survey data processed as described in Section 1 of this document.

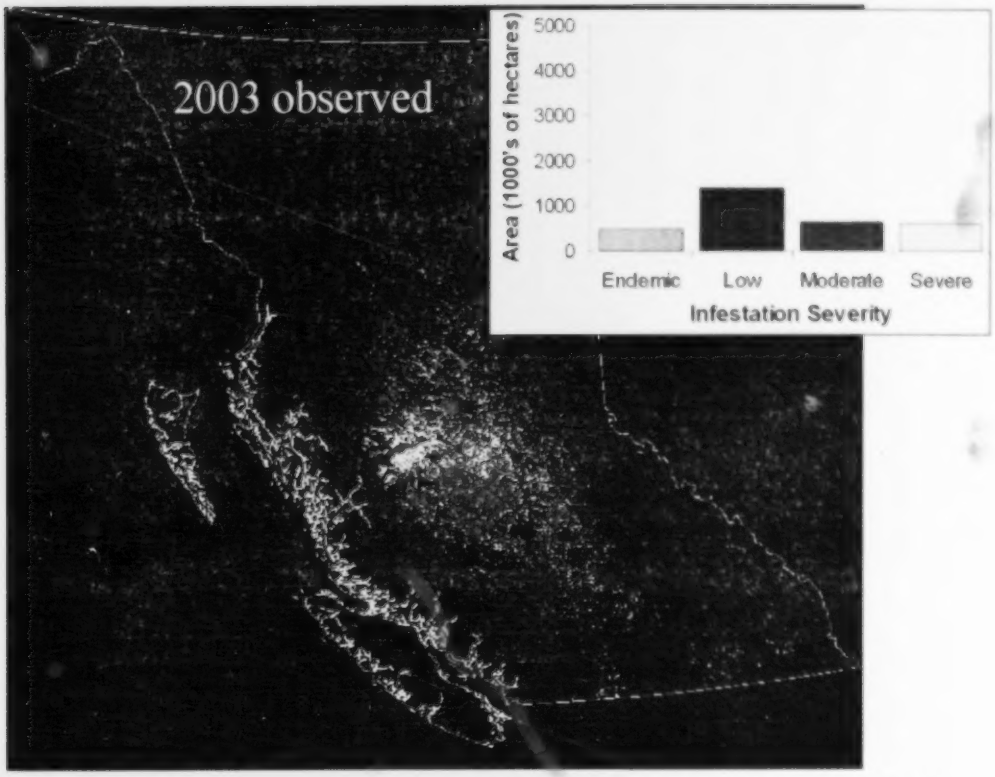

Figure 20: Mountain pine beetle infestation severity across British Columbia in 2003, according to aerial overview survey data processed as described in Section 1 of this document.

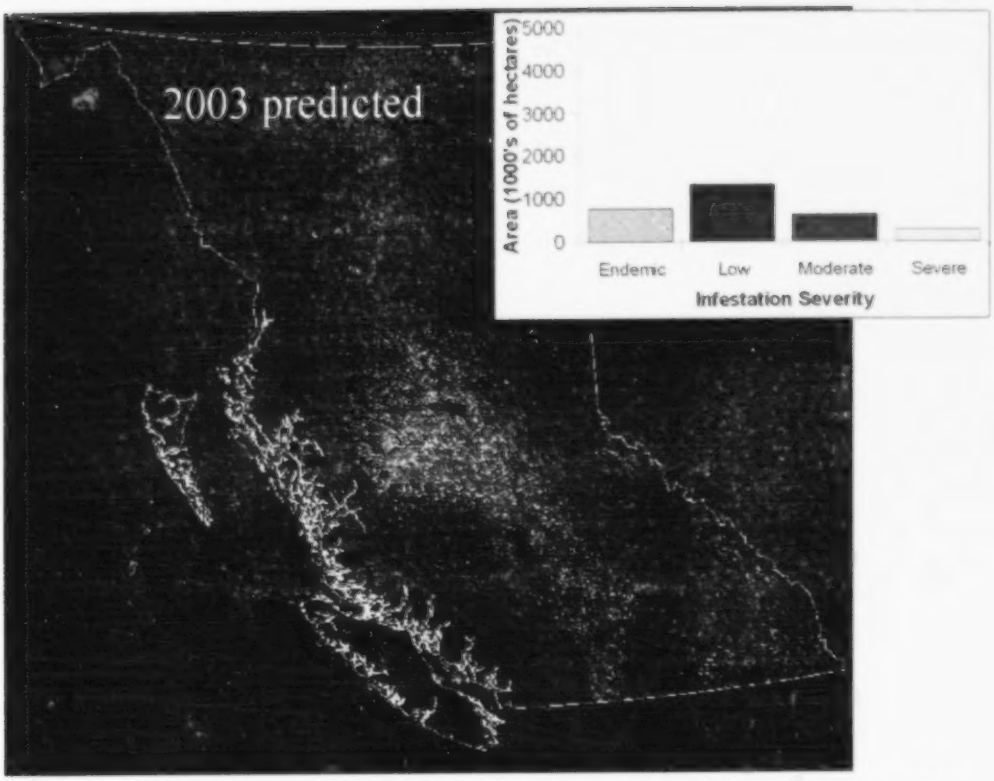

Figure 21: Mountain pine beetle severity across British Columbia in 2003, predicted by our projection model from observed mountain pine beetle severity in the preceding year (2002).

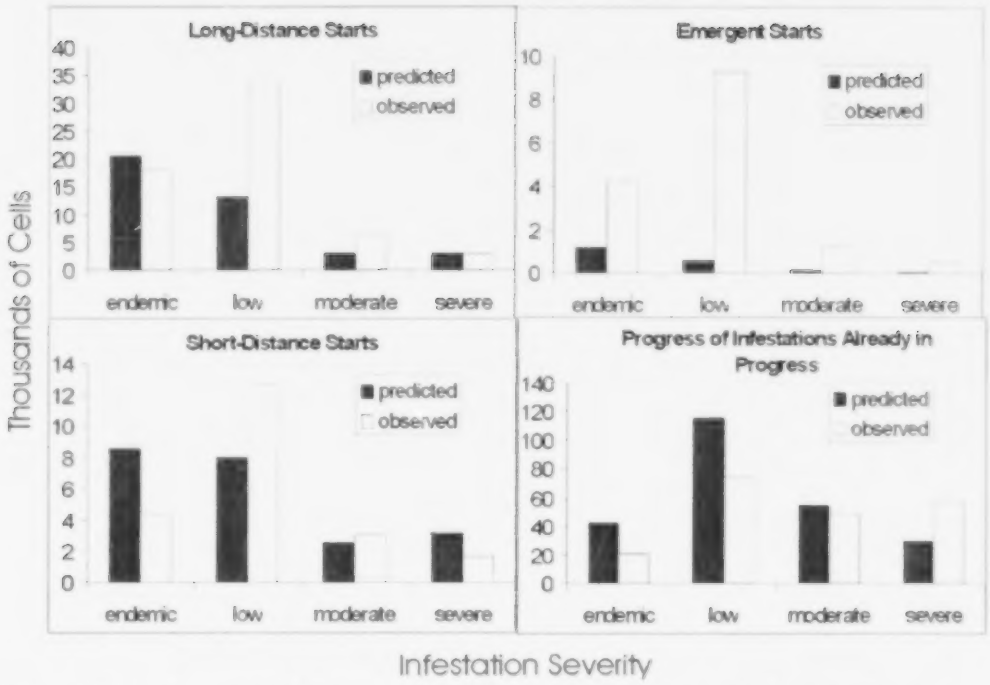

Figure 22: Performance of the projection model in each of four model sub-sections. The model under-predicts low infestation starts, emergent infestation starts of all severity, and the severity of infestation already in progress.

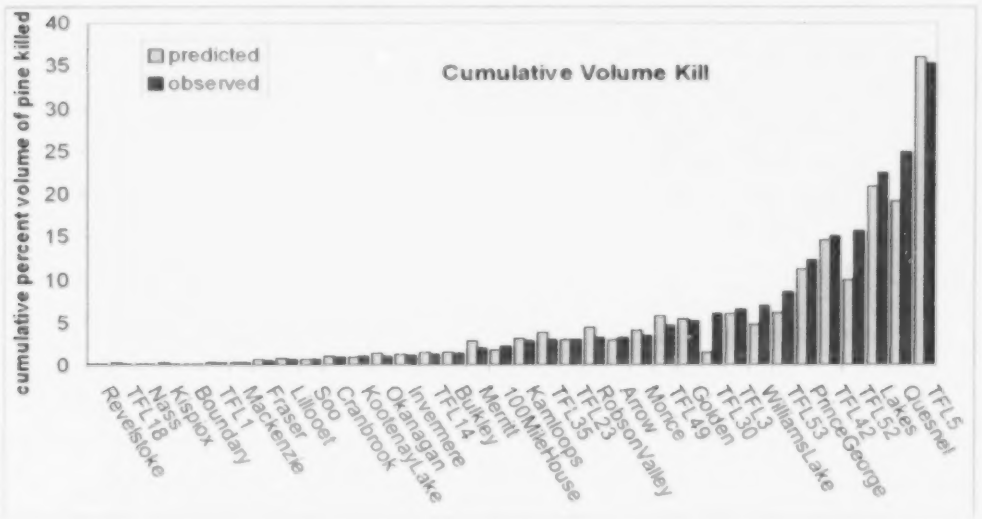

Figure 23: Variation in the performance of the projection model between mountain pine beetle management units. The model tends to under-predict volume killed in heavily infested areas, and over-predict kill in some moderately infested districts.

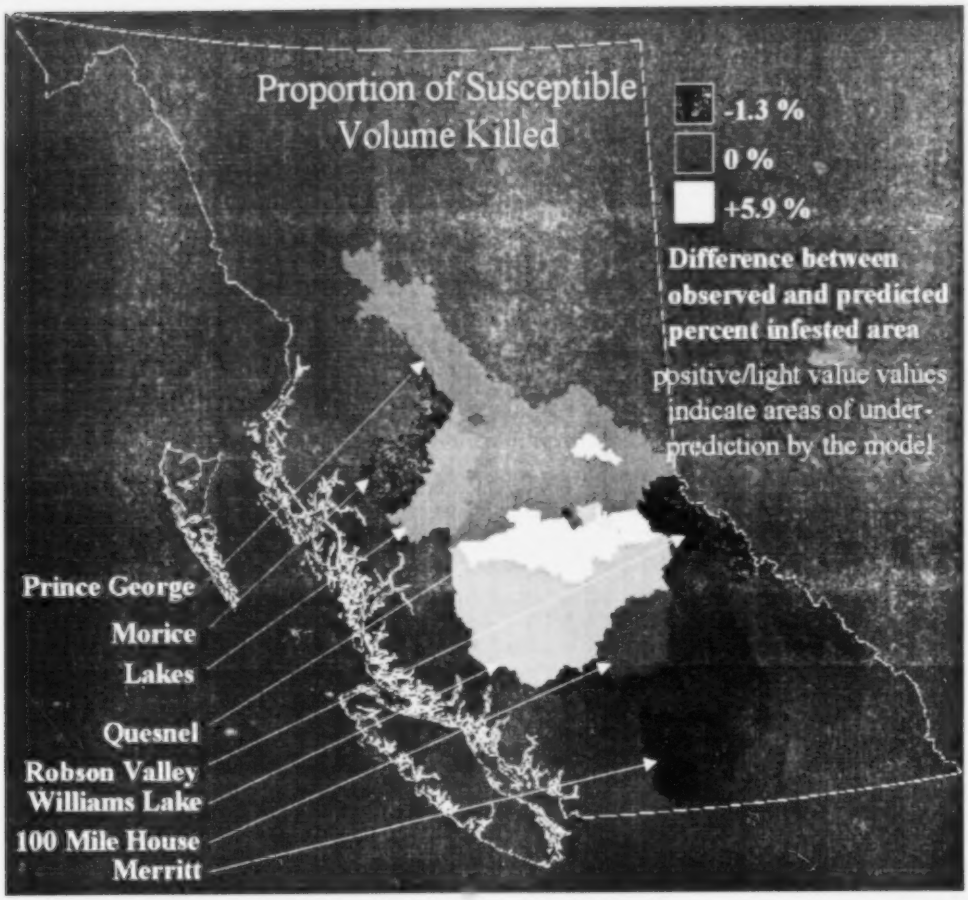

Figure 24: Spatial distribution of model errors. The model tends to under-predict near the centre of the infestation. Areas of over-prediction are scattered across the rest of the province, with no obvious spatial factor uniting them.

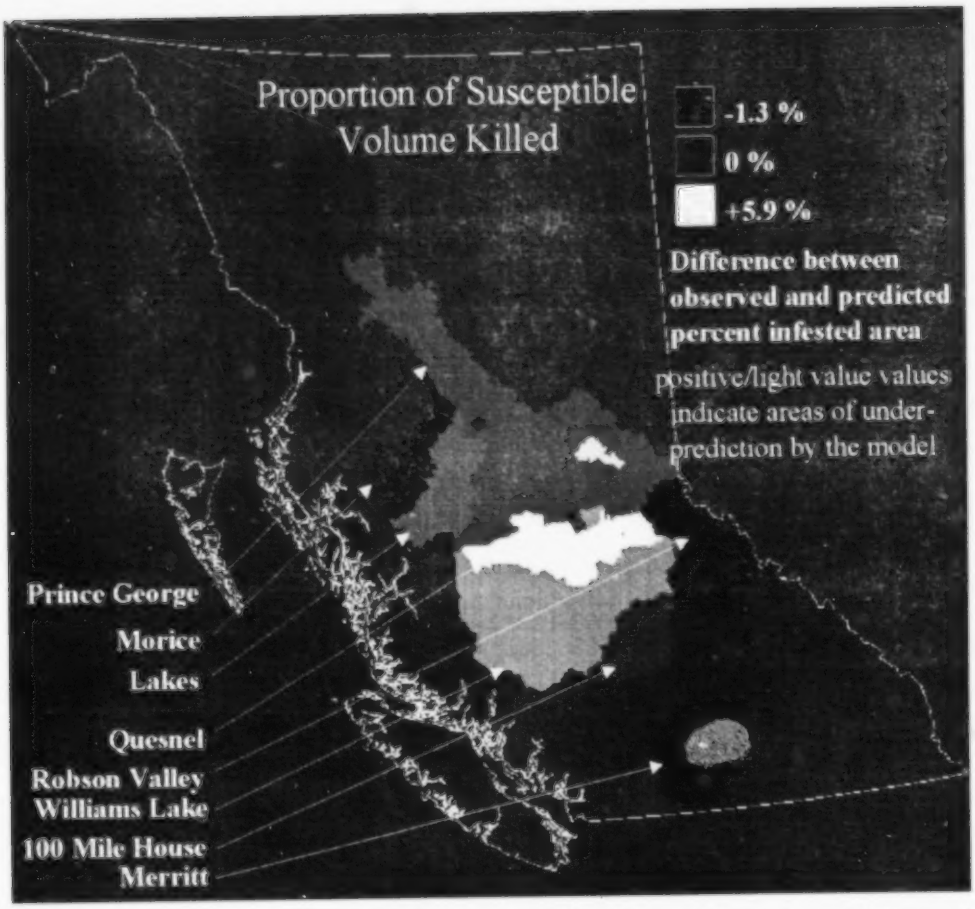

Figure 24: Spatial distribution of model errors. The model tends to under-predict near the centre of the infestation. Areas of over-prediction are scattered across the rest of the province, with no obvious spatial factor uniting them.

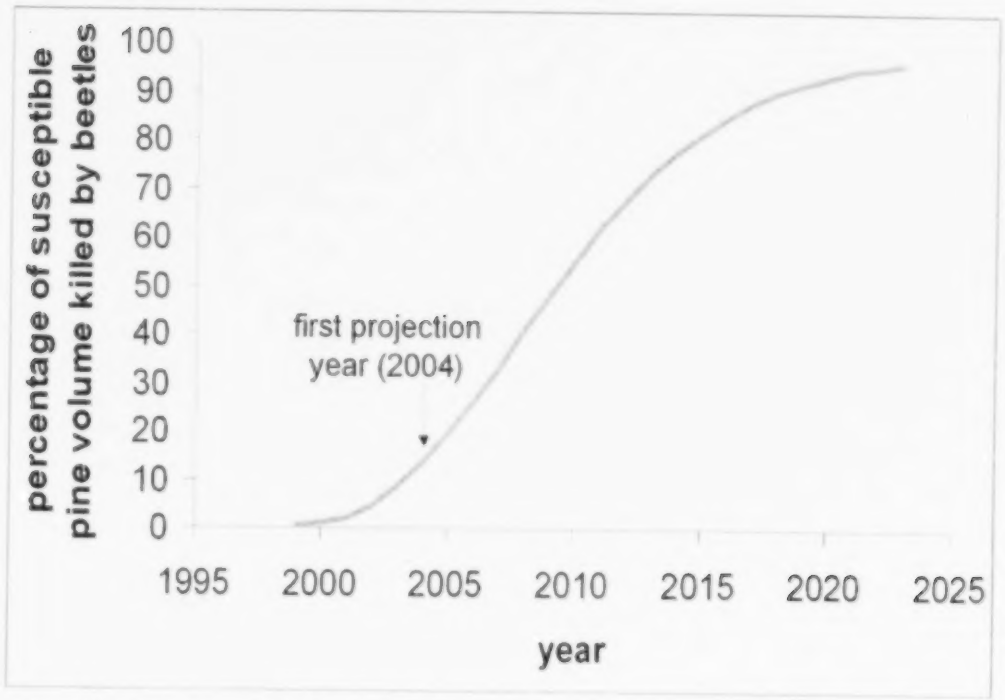

Figure 25: Long-term behaviour of the mountain pine beetle model in the absence of any management intervention. Values before 2004 are from observed data, while values after are the result of one 20-year run of the projection model starting in 2002.

Provincial-Level Projection of the Current Mountain Pine Beetle Outbreak:

An Overview of the Model (BCMPB) and Draft Results of Year 1 of the Project

Appendix 4: Indicator File Descriptions

Supported by the
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Canada

BRITISH COLUMBIA

Marvin Eng, Research Branch, BC Min. of Forests

April 2004

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Introduction

As outlined in the minutes of the first workshop held in September 2003, we identified 8 specific clients for the information being generated by this project:

- Federal government; National Forest Carbon Sinks Committee
- Forest Investment Council
- Ministry of Forests; Forest Practices Branch; Forest Health Program
- Ministry of Sustainable Resource Management; Terrestrial Information Branch
- Ministry of Water Land and Air Protection; Environmental Stewardship Division
- Ministry of Sustainable Resource Management; Planning Division
- Ministry of Forests; Forest Analysis Branch
- Ministry of Forests; Tree Improvement Branch, Gene Resource Management (GRM)

For each client the workshop identified the decisions that may be affected by the current outbreak and the information required to support the decision making processes. The workshop then identified a set of indicators that the model could produce that would be helpful in providing the information and, importantly, a domain expert that could summarize and interpret the indicator file for the appropriate decision maker.

The indicator files consist of:

- **"Strata"** that can be thought of as the rows and columns in a summary table and;
- **"Measured Values"** that can be thought of as the values that would fill the cells of the table.

For example, a common request at the workshop was to see results in the form of the area of pine affected (measured value) by cumulative impact class (strata: say the columns in a table) for each management unit (strata: say the rows in the table). Note that all indicator files include the "year of the simulation" as a strata to enable summaries over specific time frames and calculations of rates of change

Based on the discussions at the workshop and subsequent work we developed a set of indicator file specific to each client. The structure of those files was reviewed by the appropriate domain expert.

This document describes the strata and measured values available for inclusion in the indicator files and specifies the indicator file for each client. Details regarding the source and methods of creation of the data for each strata and measured value can be found in Appendix 1.

Description of Strata and Measured Values

Table 1. List of Reporting Strata and Associated Labels

Strata Name	N	Labels
Forest Management Unit	73	TSA & TFL name
Parks	850+	Park name
Resource Management Zones	3	Enhanced, IRM, Special
Caribou Range	46	Herd name
Grizzly Bear Range	60	Population name
Pine Seed Planning Zones	~100	SPZ Name
Spruce Seed Planning Zone	~100	SPZ Name
Beetle Mgmt.Units (LUs)	~1500	Landscape Unit Name
THLB/NCLB	1	Yes and No
BGC subzone/variant	192	BGC Unit name
Visual Quality Objective zones	5	Preservation, Retention, Partial Retention, Modification, Maximum Modification
Site Index Class	4	See Table 2
Inventory Type Group	42	See Table 3
Pine Species	5	See Table 4
Percent Pine Class	4	See Table 5
Age Class	12	See Table 6
Annual Impact Class	5	See Table 7
Cumulative Impact Class	7	See Table 8

Table 2. Growing Site Index (Site) classes and their descriptions

Site	Class Description	Range Site Indices
1	Poor	0
2	Low	1 - 40%
3	Moderate	41 - 80%
4	Good	91 - 100%

Note that 0 and -1 both could indicate non-forest and therefore have no site index

Table 3. Inventory Type Groups (ITG) and their descriptions

ITG Code	First Species	Second Species
Fd	Fd >80%	Any
FdCw	Fd	Cw or Yc
FdH	Fd	H B
FdS	Fd	S
FdPl	Fd	Pl
FdPy	Fd	Py
FdL	Fd	L, Pw
FdDecid	Fd	Decid
Cw	Cw/Yc >80%	Any
CwFd	Cw/Yc	Fd, L, Py, Pw, Pl, or dec.,
CwH	Cw/Yc	H, B, or S
H	H >80%	Any
HFd	H	Fd, L, Py, Pw or Pl
HCw	H	Cw or Yc
HB	H	B
HS	H	S
HDecid	H Decid	
B	B >80%	Any
BH	B	H, Cw, or Yc
BS	B	S, Fd, Pw, Pl, L, Py, or dec.
S	S >80%	Any
SFd	S	Fd, L, Pw or Py
SH	S	H, Cw or Yc
SB	S	B
SPl	S	Pl
SDecid	S	Decid
Pw	Pw	Any
Pl	Pl/Pa >80%	Any
PlFd	Pl	Fd, Pw, L, or Py
PlS	Pl	S, B, H, Cw, or Yc
PlDecid	Pl	Decid
Py	Py	Any
LFd	L	<=80% Fd
L	L	Any (Fd when L>80%)
AcConif	Ac	Conif
AcDecid	Ac	Decid
DrConif	Dr	Conif
DrDecid	Dr	Decid
Mb	Mb	Any
E	E	Any
AtConif	At	Conif
AtDecid	At	Decid

Table 4. Common names of pine species used and the associated latin names

Common Name	*Latin Name*
Limber Pine	*Pinus flexilis*
Lodgepole Pine	*Pinus contorta*
Western White Pine	*Pinus monticola*
Whitebark Pine	*Pinus albicaulis*
Ponderosa Pine	*Pinus ponderosa*

Table 5. Percent Pine Class (PctPineCls) classes and their descriptions.

PctPineCls	Class Description	Range of Percent Pine
0	No Pine	0
1	Low	1 - 40%
2	Moderate	41 - 80%
3	High	91 - 100%

Table 6. Age Class (AgeCls) classes and their descriptions.

AgeCls	Lower Limit of Age Class (years)
0	0
1	20
2	40
3	60
4	80
5	100
6	120
7	140
8	160
9	180
10	200
11	> 200

Table 7. Annual severity of beetle infestation (annSevCls) classes and their descriptions.

annSevCls	Class Description	Percent Kill Range	Mid Point of Percent Kill
0	No MPB	0	0%
1	Endemic	<1%	0.5%
2	Low	1 - 10 %	5%
3	Moderate	11 -20%	15%
4	Severe	21 -50 %	35%

Table 8. Cumulative severity of beetle infestation (cumSevCls) classes and their descriptions.

cumSevCls	Class Description	Percent Kill Range	Mid Point of Percent Kill
0	No MPB	0	0%
1	Endemic	<1%	0.5%
2	Low	1 - 10 %	5%
3	Moderate	11 -20%	15%
4	Severe	21 -50 %	35%
5	Very Severe	51 - 75 %	63%
6	Complete Kill	76 - 100 %	88%

Table 9. Measured values available for the indicator files.

Measured Values	Units
Land Area	ha
Forest Area	ha
Pine Area (% pine weighted)	ha
Green Harvest Area	ha/yr
Salvage Harvest Area	ha/yr
Volume Total	m^3
Pine Volume	m^3
Volume of Green Harvest	m^3/year
Volume of Salvage 0 - 5 years old	m^3/year
Volume of Salvage 6 - 10 years old	m^3/year
Volume of Salvage 11 - 15 years old	m^3/year
Volume of Non Recovered Losses	m^3/year

Note that the pine area reported is weighted by the percent pine in a stand. I.E. 100 hectares of 10% pine would be reported as 10 hectares. The "full" area of forest with any pine can be obtained through combinations of the measured value Forest Area and either the Pine Species or Percent Pine strata.

Client Specific Indicator Files

Table 10. Indicator file for the Federal government; National Forest Carbon Sinks Committee.

Strata
Forest Management Unit
BGC subzone/variant
Percent Pine Class
Annual Impact Class
Cumulative Impact Class

Measured Values
Land Area
Forest Area
Pine Area (% pine weighted)
Volume Total
Pine Volume

Table 11. Indicator file for the Forest Investment Council – Site Rehabilitation

Strata
Forest Management Unit
THLB/NCLB
Site Index Class
Inventory Type Group
Pine Species
Percent Pine Class
Age Class
Annual Impact Class
Cumulative Impact Class

Measured Values
Land Area
Forest Area
Pine Area (% pine weighted)
Volume Total
Pine Volume
Volume of Non Recovered Losses

Table 12. Indicator file for the Ministry of Forests; Forest Practices Branch; Forest Health Program

Strata
Forest Management Unit
Parks
Beetle Mgmt.Units (LUs)
Percent Pine Class
Age Class
Annual Impact Class
Cumulative Impact Class

Measured Values
Land Area
Forest Area
Pine Area (% pine weighted)
Volume Total
Pine Volume
Volume of Non Recovered Losses

Table 13. Indicator file for the Ministry of Sustainable Resource Management; Terrestrial Information Branch.

Strata
Forest Management Unit
Beetle Mgmt.Units (LUs)
THLB/NCLB
Percent Pine Class
Annual Impact Class
Cumulative Impact Class

Measured Values
Land Area
Forest Area
Pine Area (% pine weighted)
Volume Total
Pine Volume

Table 14. Indicator file for the Ministry of Water Land and Air Protection; Environmental Stewardship Division.

Strata
Forest Management Unit
Parks
Caribou Range
Grizzly Bear Range
Ungulate Winter Ranges
Beetle Mgmt.Units (LUs)
BGC subzone/variant
Inventory Type Group
Pine Species
Percent Pine Class
Age Class
Annual Impact Class
Cumulative Impact Class

Measured Values
Land Area
Forest Area
Pine Area (% pine weighted)
Green Harvest Area
Salvage Harvest Area

Table 15. Indicator file for the Ministry of Sustainable Resource Management; Planning Division.

Strata
Name
Forest Management Unit
Parks
Resource Management Zones
Beetle Mgmt.Units (LUs)
Percent Pine Class
Age Class
Annual Impact Class
Cumulative Impact Class

Measured Values
Value
Land Area
Forest Area
Pine Area (% pine weighted)

Table 16. Indicator file for the Ministry of Forests; Forest Analysis Branch.

Strata
Name
Forest Management Unit
THLB/NCLB
Site Index Class
Percent Pine Class
Age Class
Annual Impact Class
Cumulative Impact Class

Measured Values
Value
Land Area
Forest Area
Pine Area (% pine weighted)
Green Harvest Area
Salvage Harvest Area
Volume Total
Pine Volume
Volume of Green Harvest
Volume of Salvage 0 - 5 years old
Volume of Salvage 6 - 10 years old
Volume of Salvage 11 - 15 years old
Volume of Non Recovered Losses

Table 17. Indicator file for the Ministry of Forests; Tree Improvement Branch, Gene Resource Management (GRM).

Strata
Name
Forest Management Unit
Seed Planning Zones
Annual Impact Class
Cumulative Impact Class

Measured Values
Value
Land Area
Forest Area
Pine Area (% pine weighted)

Provincial-Level Projection of the Current Mountain Pine Beetle Outbreak:

An Overview of the Model (BCMPB) and Draft Results of Year 1 of the Project

Appendix 5. Verification and Sensitivity of the Beetle Projection Sub-Model

Supported by the
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and the BC Forest Service

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BRITISH COLUMBIA

Marvin Eng, Research Branch, BC Min. of Forests
Andrew Fall, Gowlland Technologies Ltd.
Josie Hughes, Research Consultant

April 2004

We developed the beetle projection model using data from 1999 to 2002 inclusive, reserving 2003 as a verification year. Out of curiousity, we also projected forward from 1999 to see how model errors might compound over time. Over the period from 1999 to 2003 the outbreak escalates somewhat faster than our model predicts (Figure 1). That is, we overpredict the growth of the outbreak in 2000 and 2001, and underpredict in 2002 and 2003. In 2003, we predict that 39 million m^3 are killed by beetles (a 77% increase in cumulative volume killed), while the data shows 52 million m^3 (a 100% increase in cumulative volume killed). Our concern about this discrepancy is moderated by our belief that (even after our modifications) the overview survey data still overestimates the volume killed by beetles.

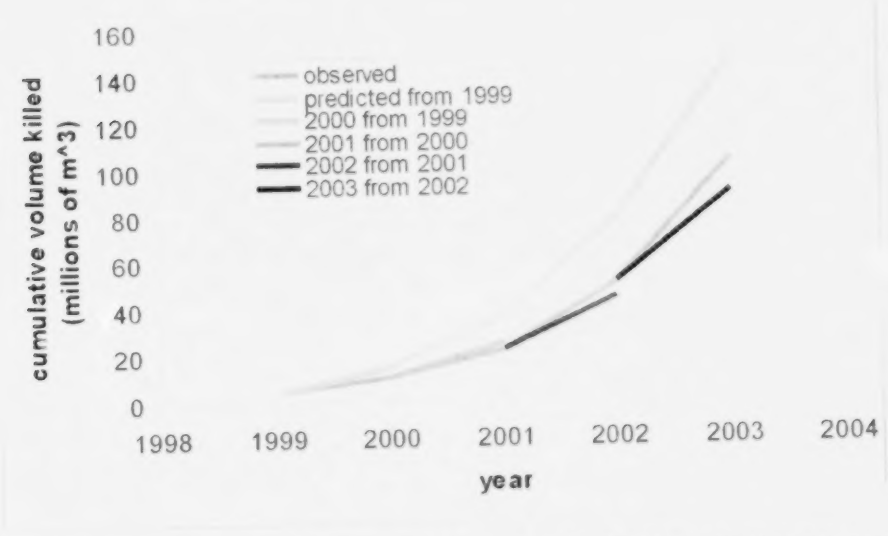


Figure 1. Province-wide performance of mountain pine beetle projection model. The model here is parameterized with data from 1999 to 2003.

The provincial-scale volume comparisons are interesting, but to not give us any real insight into how the model is behaving. For this, we turned to a more detailed comparison of observed and predicted outbreak dynamics in 2003. Aspatially, the two main differences between our model prediction and the data are: we underpredict the number of new low-severity infestations (Figure 2), and underpredict the number of infestations in progress that remain severe (Figure 3).

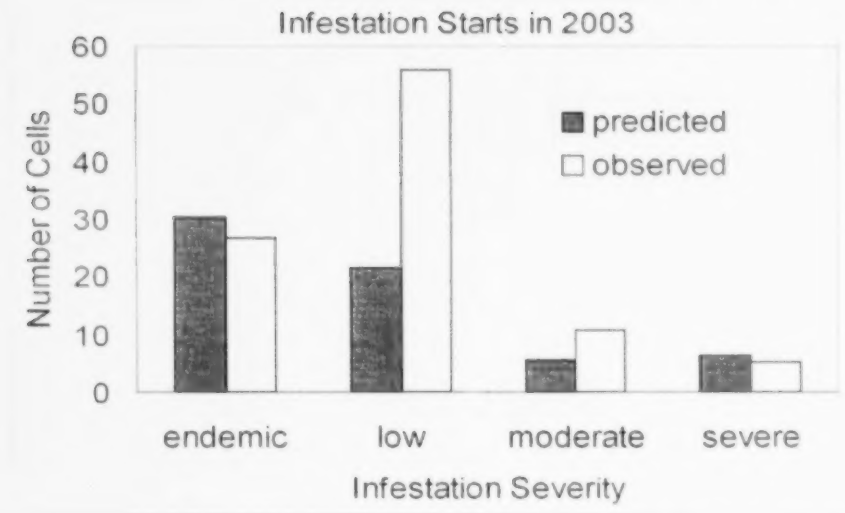


Figure 2. Comparison of behaviour of infestation start sub-model to observed infestations starts in 2003.

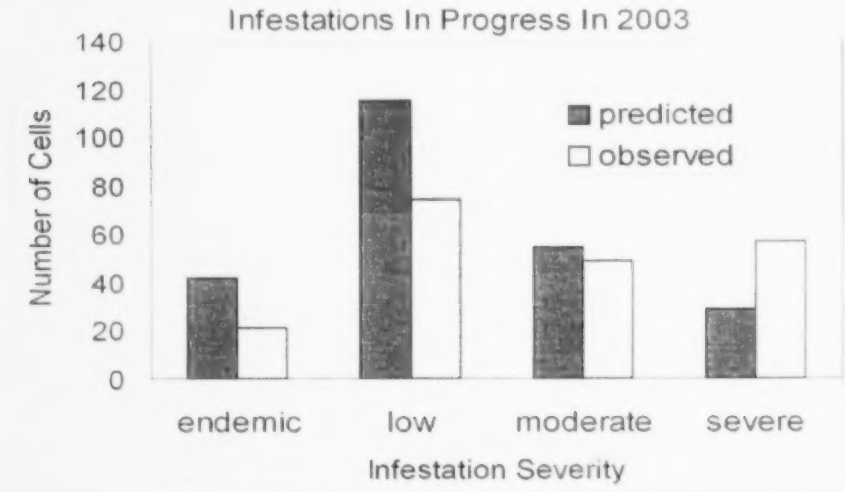


Figure 3. Comparison of behaviour of infestation progress sub-model to the observed progress of infestations in 2003.

A quick comparison of our projected map (Figure 4) to the observed distribution of beetles (Figure 5) shows that fail to predict the correct number of low infestation starts because we fail to predict the large area of the Chilcotin that became infested in 2003. First, we note that the land in this area is apparently 1-2% infested, putting it at the bottom end of the low severity class (Ebata and Westfall, personal communication). We also note that the rapid movement of beetles into this area is somewhat anomalous, given the progress of the infestation over the preceding four years. So our failure to predict this

Chilcotin outbreak underlines an inherent limitation of the beetle projection model as we have formulated it – we predict that the outbreak will continue to spread as it has since 1999. We do not include major stochastic events such as cold weather or strong winds, and we cannot unprecedented spread patterns.

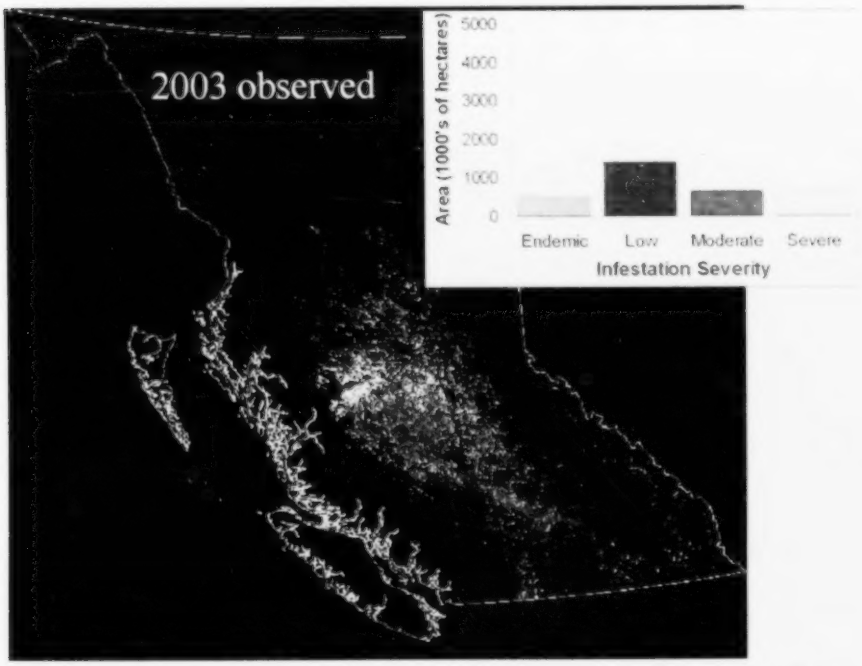


Figure 4. Observed overview of mountain pine beetle infestations in 2003.

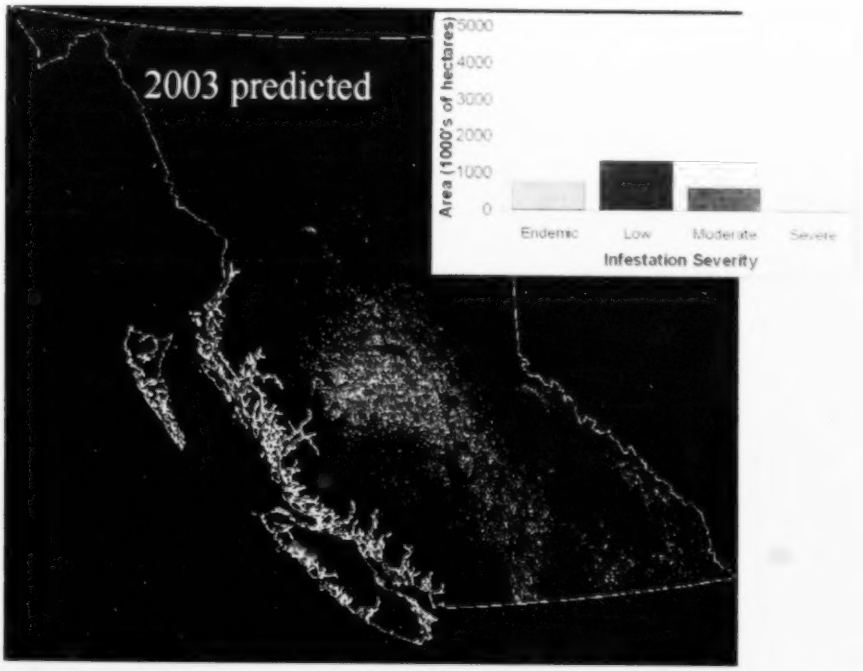


Figure 5. Predicted overview of mountain pine beetle infestations across in 2003.

By management unit, the projection model predicts lower amounts of kill than the data shows in heavily infested districts such as Quesnel, Lakes, Prince George, and Williams Lake (Figure 6). This is not a surprise, nor do we find it particularly concerning. Of more interest are the areas with fewer beetles where we significantly over-predict kill. These areas include Robson Valley, Merritt, Okanagan, Morice, and Mackenzie. In Robson Valley and Mackenzie, it may be that the overview survey under-reports the actual amount of beetle activity, so our predictions are not as wrong as they appear. In Morice and the more southern management units, beetles have been simmering away for a long period, and the dynamics in these areas might be different than in the parts of province where the beetle outbreak is a more recent phenomenon. We thank the participants in our March workshop for these insights and others. We will focus in the coming year on more thoroughly investigating the possibilities.

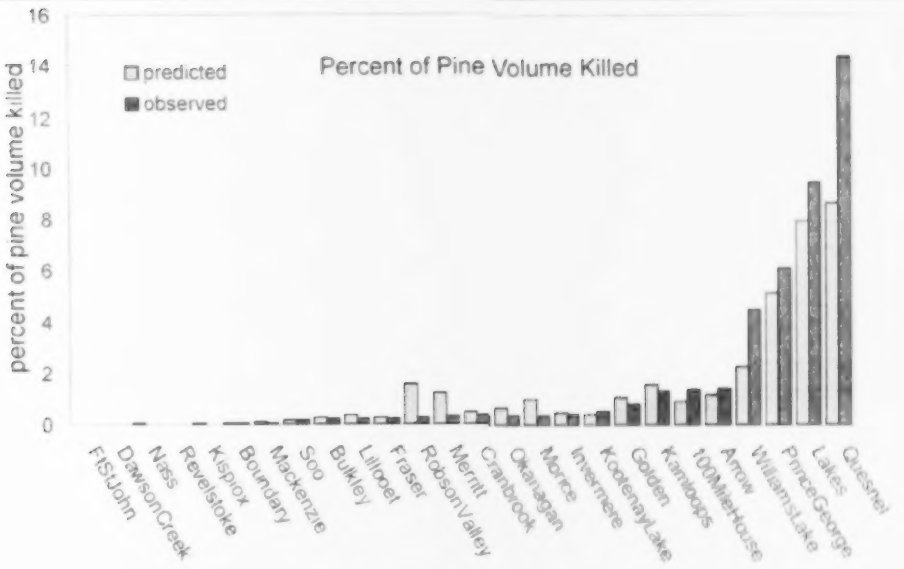


Figure 6. Performance of the mountain pine beetle projection model by management unit.

We have several major areas of uncertainty in our beetle model, including: Over what scale does the presence of current infestations affect the probability of new infestations arising? How far away must a new infestation be from other infestations before we reasonably assume that the infestation has arisen independently?; And once an infestation has subsided, what happens? Under what conditions, if any, might it restart?

We do not know the answers to these questions, but we can investigate the consequences of alternative assumptions. In brief, we found that changing our assumption about the scale at which infestations might be considered emergent has almost not effect on the annual amount of pine killed (Figure 7) nor the cumulative amount of pine killed (Figure 8). This is because the outbreak has by now progressed so far that most pine forest in the province is by now quite close to infested areas. If we started in 1999, when beetles were less thoroughly distributed, our assumption about the scale of influence would make more difference.

In contrast, the model is quite sensitive to our assumption about whether or not infestations are allowed to "re-start" in cells where they have completely subsided, given sufficient local beetle pressure and some remaining host.

Feedback at a recent workshop on the modeling approach described here indicated that we should devote significant effort to this question of stopping conditions, so we will focus on this in the coming months.

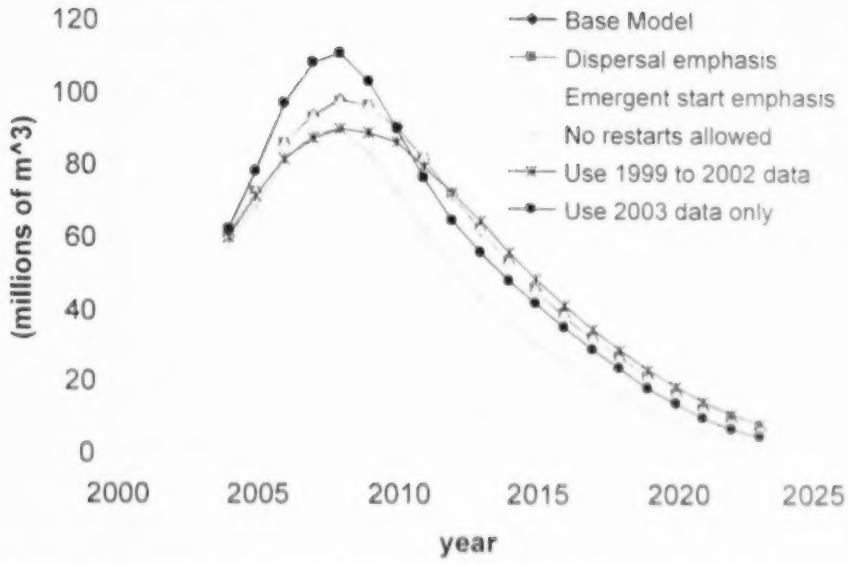


Figure 7. Sensitivity of projections of annual kill of pine on the THLB to various beetle model parameters (No Management Scenario).

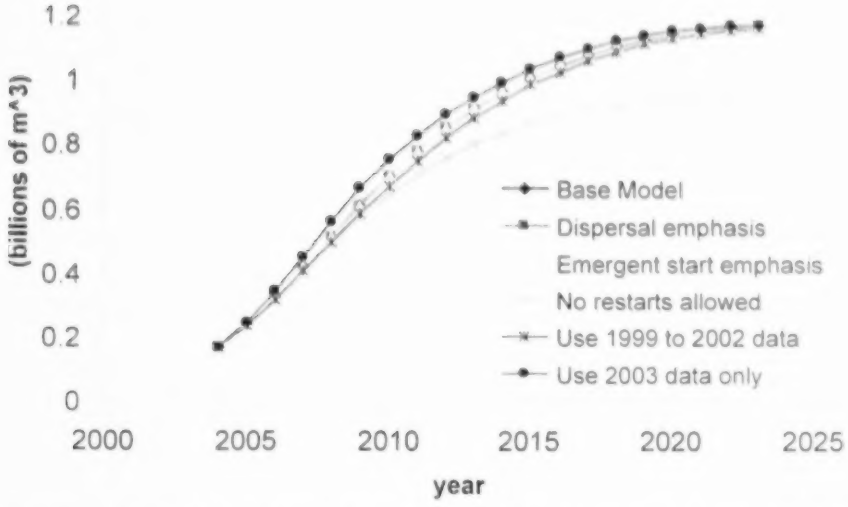
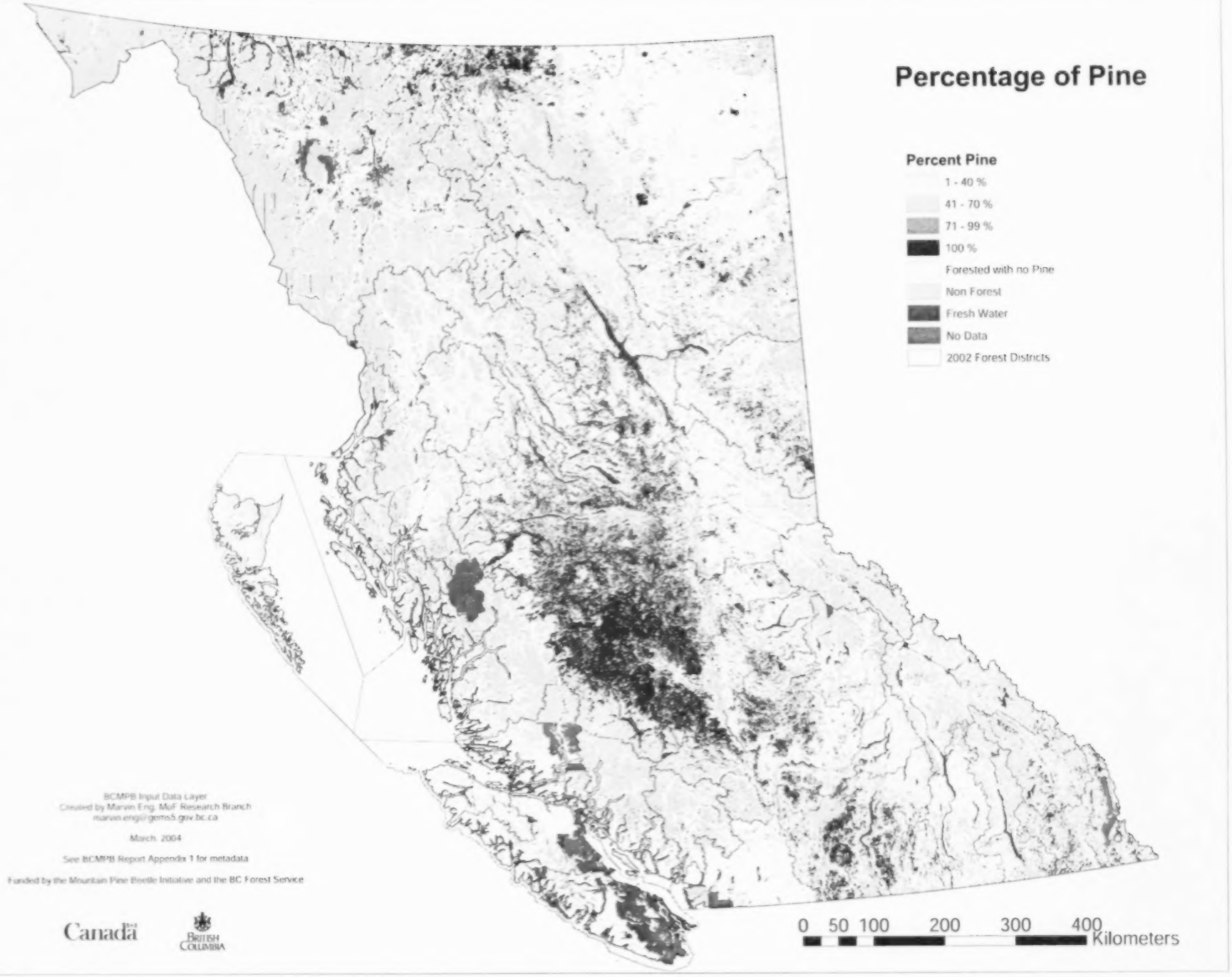
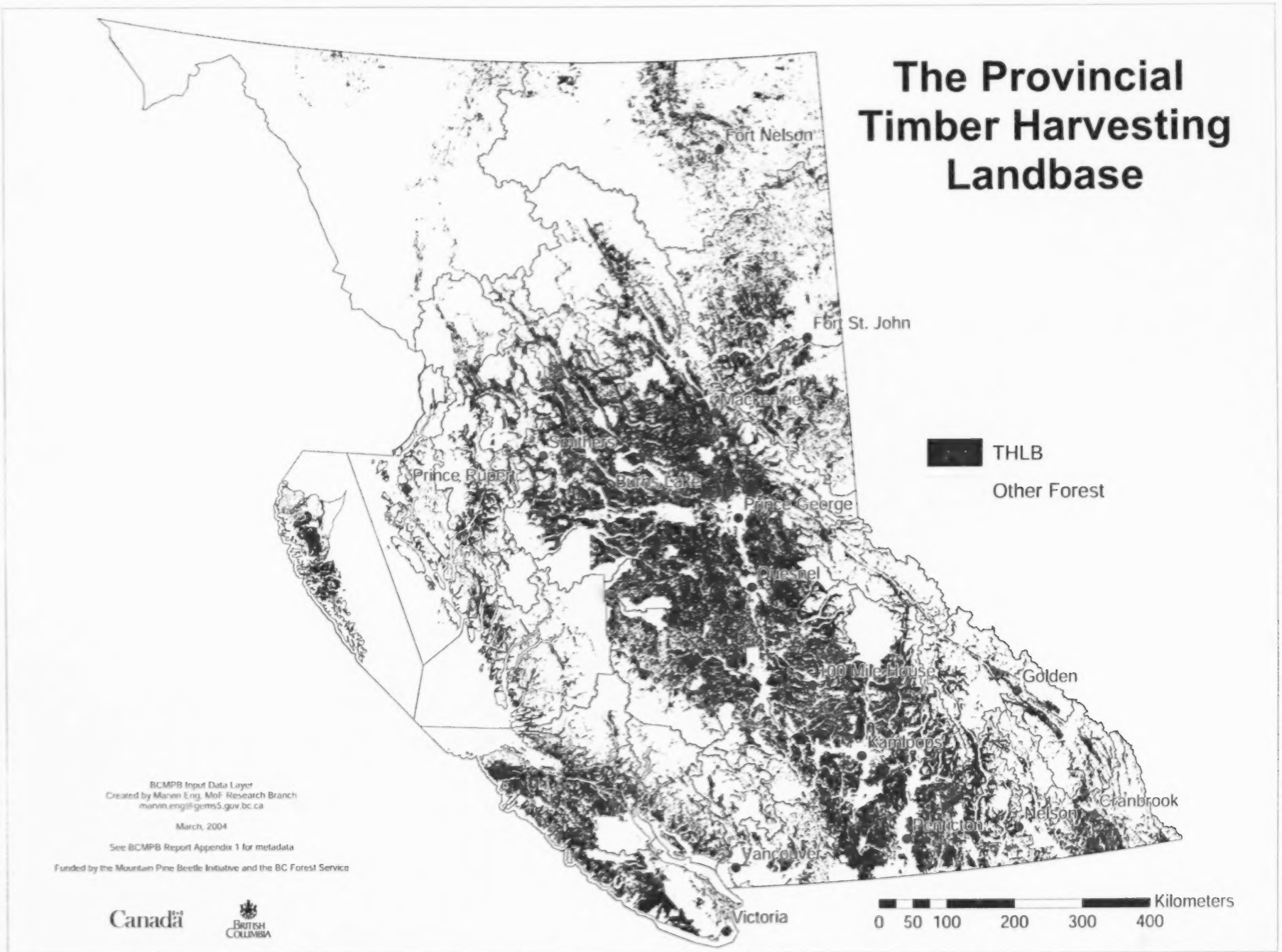


Figure 8. Sensitivity of projections of cumulative kill of pine on the THLB to various beetle model parameters (No Management Scenario).


Percentage of Pine
Percent Pine
1 - 40 %
41 - 70 %
71 - 99 %
100 %
Forested with no Pine
Non Forest
Fresh Water
No Data
2002 Forest Districts
BCMPB Input Data Layer
Created by Marvin Eng, MoF Research Branch
marvin.eng@gems5.gov.bc.ca
March, 2004
See BCMPB Report Appendix 1 for metadata
Funded by the Mountain Pine Beetle Initiative and the BC Forest Service
Canada
British Columbia
0 50 100 200 300 400
Kilometers


The Provincial Timber Harvesting Landbase
Fort Nelson
Fort St. John
Mackenzie
Smithers
Prince Rupert
Burns Lake
Prince George
Quesnel
100 Mile House
Golden
Kamloops
Cranbrook
Nelson
Penticton
Vancouver
Victoria
THLB
Other Forest
Kilometers
0 50 100 200 300 400
BCMPB Input Data Layer
Created by Marvin Eng, MoF Research Branch
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March, 2004
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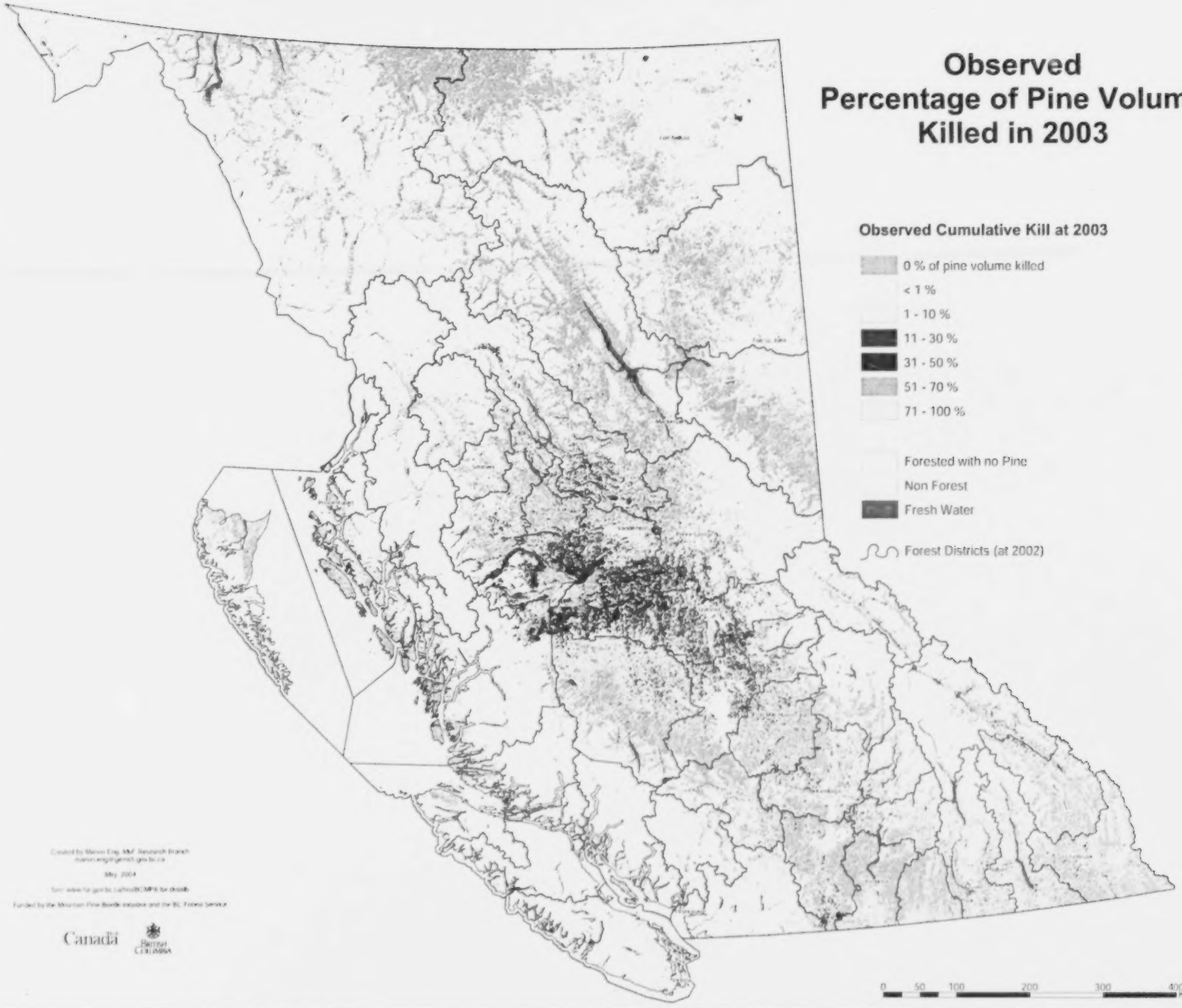
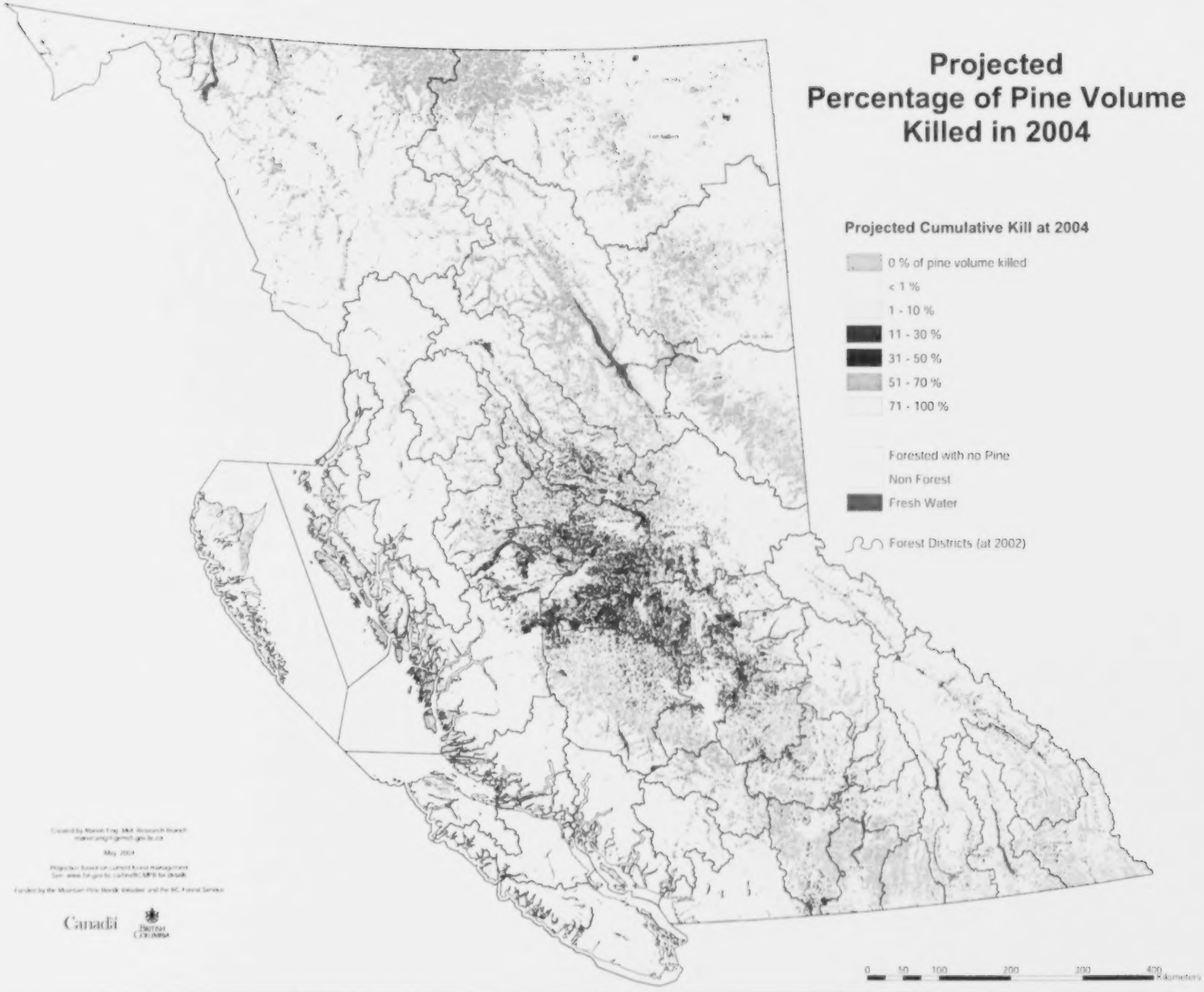
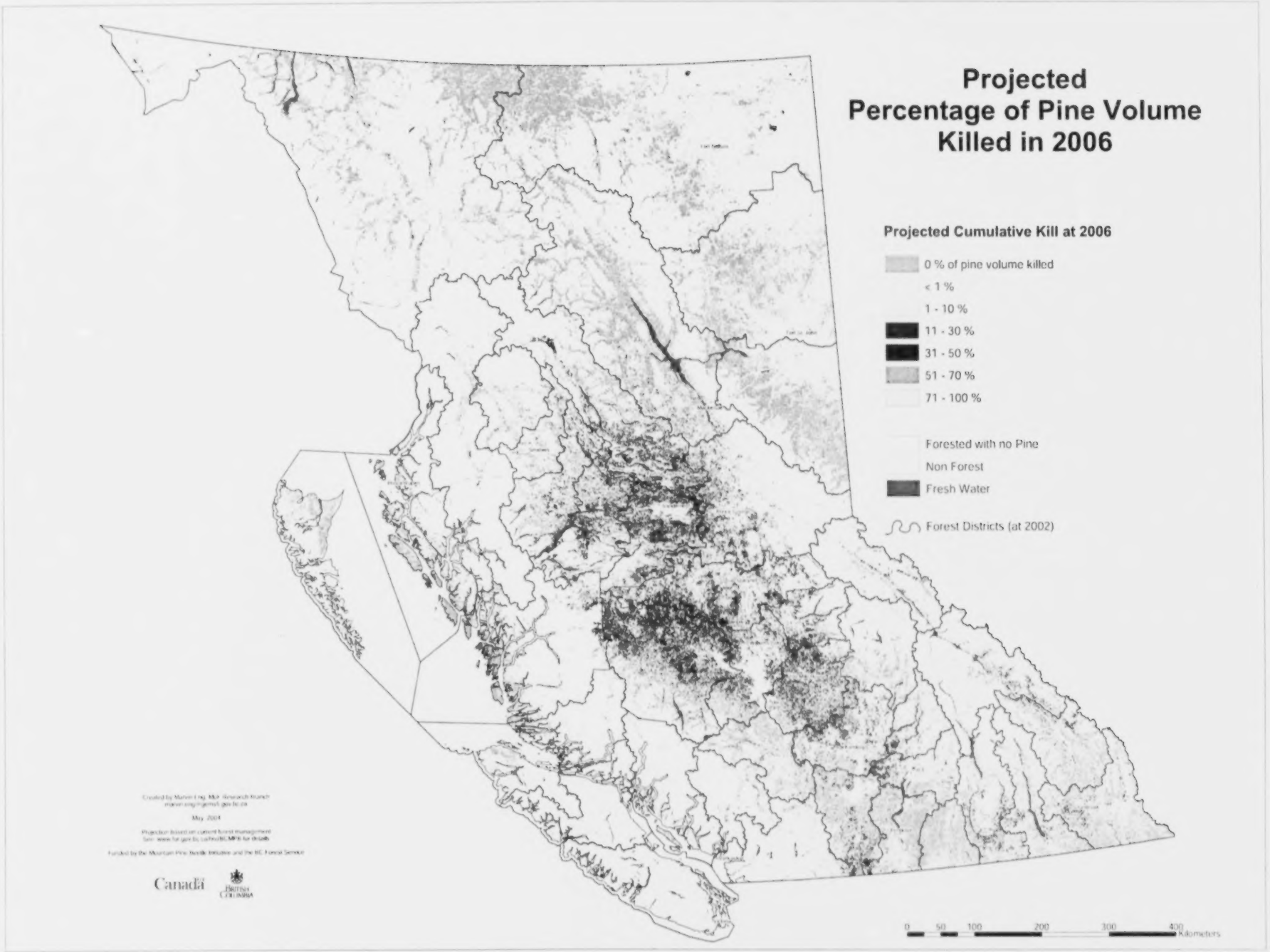
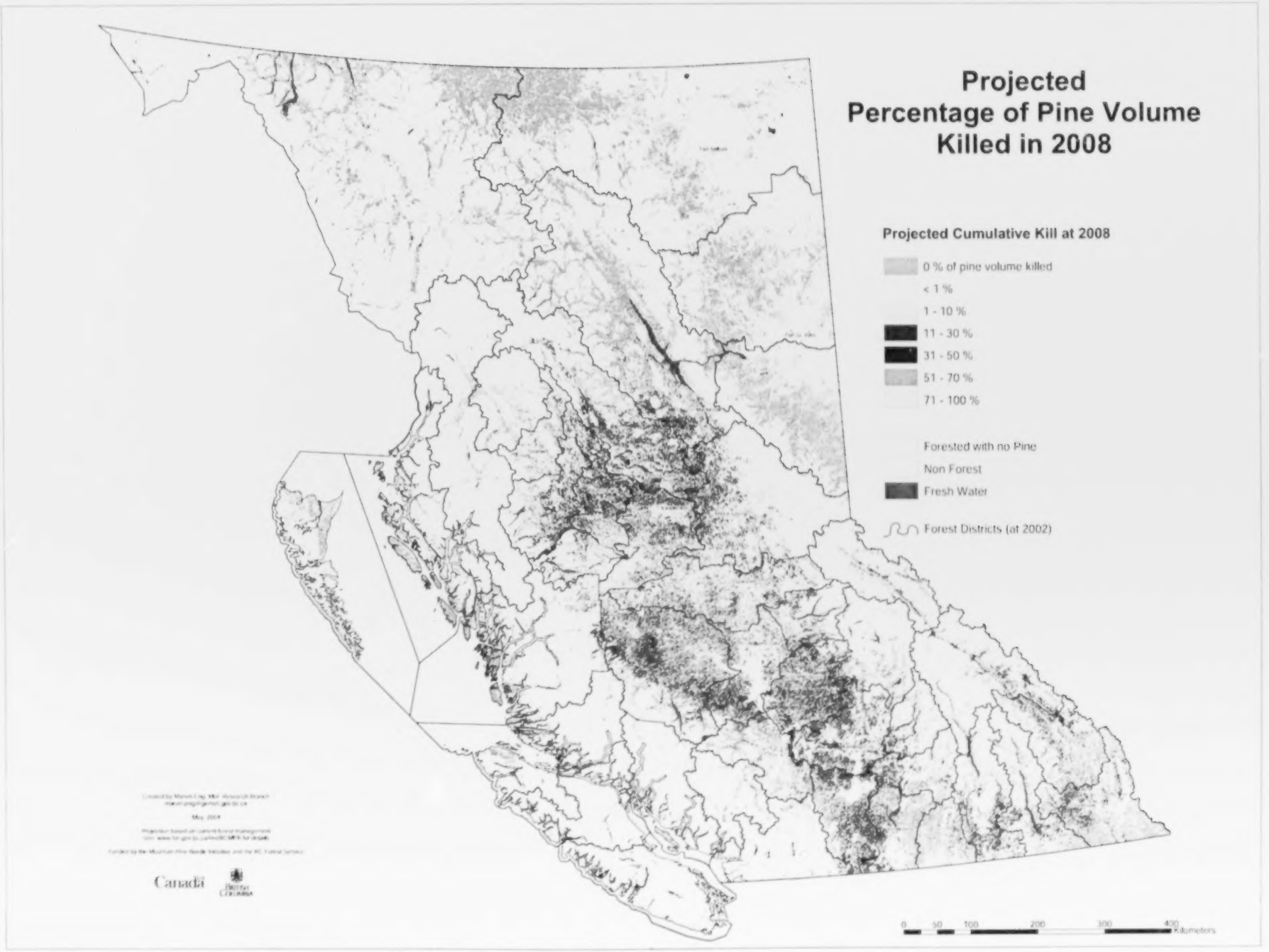
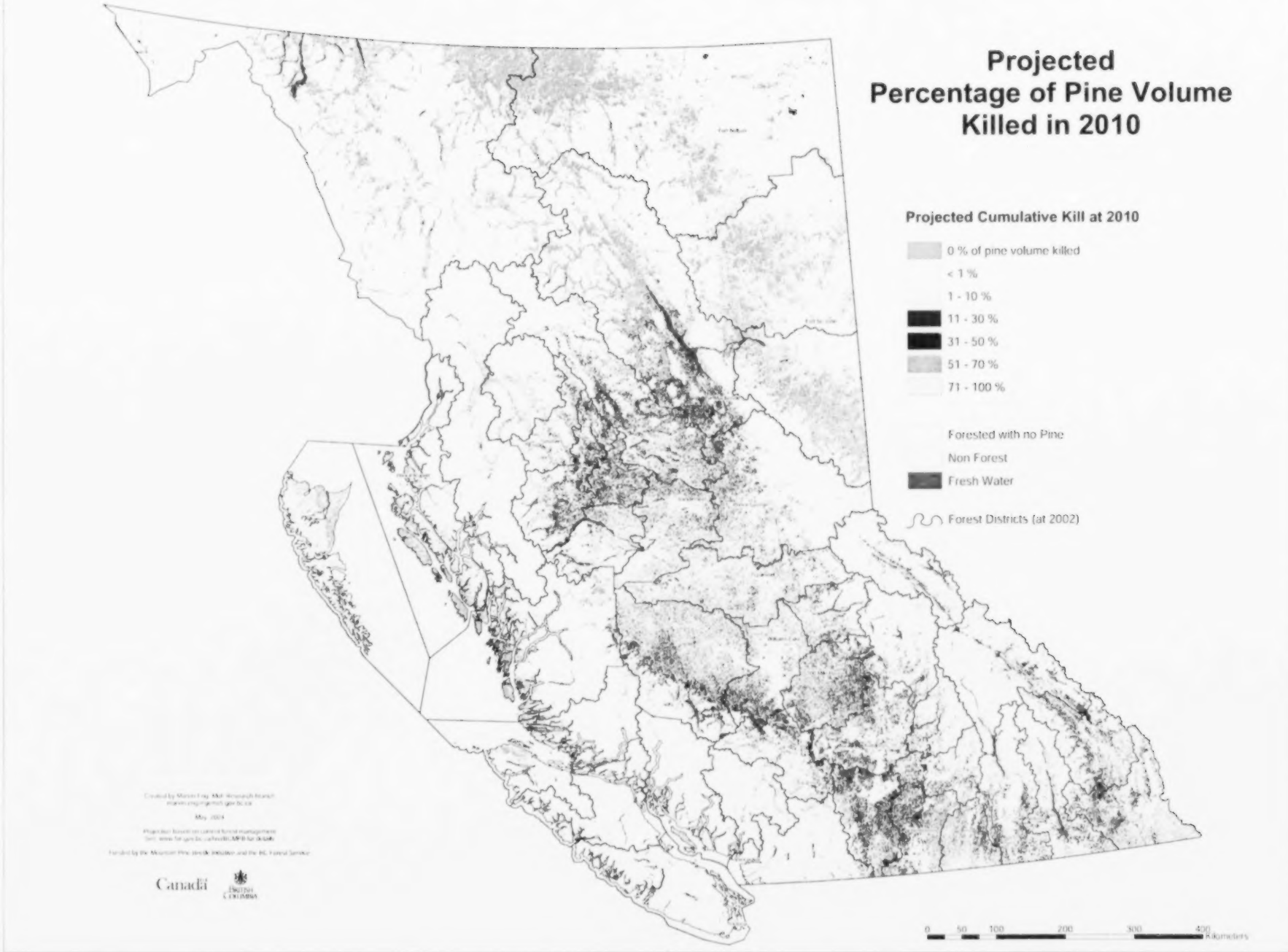

Observed
Percentage of Pine Volume
Killed in 2003
Observed Cumulative Kill at 2003
0 % of pine volume killed
< 1 %
1 - 10 %
11 - 30 %
31 - 50 %
51 - 70 %
71 - 100 %
Forested with no Pine
Non Forest
Fresh Water
Forest Districts (at 2002)
0 50 100 200 300 400 Kilometers
May 2004
Canada
CE BLANSA


Projected
Percentage of Pine Volume
Killed in 2004
Projected Cumulative Kill at 2004
0 % of pine volume killed
< 1 %
1 - 10 %
11 - 30 %
31 - 50 %
51 - 70 %
71 - 100 %
Forested with no Pine
Non Forest
Fresh Water
Forest Districts (at 2002)
0 50 100 200 300 400
Kilometers


Projected
Percentage of Pine Volume
Killed in 2006
Projected Cumulative Kill at 2006
0 % of pine volume killed
< 1 %
1 - 10 %
11 - 30 %
31 - 50 %
51 - 70 %
71 - 100 %
Forested with no Pine
Non Forest
Fresh Water
Forest Districts (at 2002)
0 50 100 200 300 400
Kilometers
May 2004
Canada
BRITISH COLUMBIA


Projected
Percentage of Pine Volume
Killed in 2008
Projected Cumulative Kill at 2008
0 % of pine volume killed
< 1 %
1 - 10 %
11 - 30 %
31 - 50 %
51 - 70 %
71 - 100 %
Forested with no Pine
Non Forest
Fresh Water
Forest Districts (at 2002)
0 50 100 200 300 400
Kilometers
May, 2004
Canada
British Columbia


Projected
Percentage of Pine Volume
Killed in 2010
Projected Cumulative Kill at 2010
0 % of pine volume killed
< 1 %
1 - 10 %
11 - 30 %
31 - 50 %
51 - 70 %
71 - 100 %
Forested with no Pine
Non Forest
Fresh Water
Forest Districts (at 2002)
Canada
BRITISH COLUMBIA
0 50 100 200 300 400 Kilometers